



Air Quality & Meteorology

**Class I Annual NO₂ SIL
Evaluation**



Class I Annual NO₂ SIL Evaluation

Prepared for

Epsilon Associates
3 Mill & Main Place, Suite 250
Maynard, MA 01754

Prepared by

Exponent
1 Mill and Main Place, Suite 150
Maynard, MA 01754

April 2019

© Exponent, Inc.

Doc. no. 1808644.000 - 2691

Contents

	<u>Page</u>
List of Figures	iii
List of Tables	v
Acronyms and Abbreviations	vi
Limitations	vii
1 CALPUFF Class I Simulations	8
1.1 Purpose	8
1.2 Model Selection	8
1.3 Source Data	9
1.4 Meteorological Data	9
1.5 Model Domain	10
1.6 Class I Receptors	10
1.7 CALPUFF Configuration	10
1.8 Annual NO ₂ Project Impacts	15
2 WRF Performance Evaluation	16
2.1 Performance Criteria	16
2.2 Observed Meteorological Data	17
2.3 Model Performance	22
2.3.1 Wind Speed and Direction	22
2.3.2 Temperature	37
2.3.3 Specific Humidity	42
2.3.4 Conclusions	42
3 References	47
Appendix A Lakes WRF Model Documentation	

List of Figures

	<u>Page</u>
Figure 1 CALPUFF modeling domain and modeled Class I areas.	11
Figure 2 Class I Area Receptors for Brigantine Wilderness Area	12
Figure 3 Class I Area Receptors for Lye Brook	13
Figure 4 Class I Area Receptors for Presidential Range – Dry River	14
Figure 5 Observational stations within the modeling domain including surface stations (pink) and overwater stations (blue).	21
Figure 6 WRF predicted wind fields for year 2015	24
Figure 7 Observed wind fields for year 2015	25
Figure 8 WRF predicted wind fields for year 2016	26
Figure 9 Observed wind fields for year 2016	27
Figure 10 WRF predicted wind fields for year 2017	28
Figure 11 Observed wind fields for year 2017	29
Figure 12 Observed and modeled wind speeds for Martha’s Vineyard January 2015.	31
Figure 13 Observed and modeled wind speeds for Martha’s Vineyard July 2015.	31
Figure 14 Observed and modeled wind direction for Martha’s Vineyard January 2015.	32
Figure 15 Observed and modeled wind direction for Martha’s Vineyard July 2015.	32
Figure 16 Observed and modeled wind speeds for Worcester January 2015.	33
Figure 17 Observed and modeled wind speeds for Worcester July 2015.	33
Figure 18 Observed and modeled wind direction for Worcester January 2015.	34
Figure 19 Observed and modeled wind direction for Worcester July 2015.	34
Figure 20 Observed and modeled wind speeds for Rutland, VT January 2015.	35
Figure 21 Observed and modeled wind speeds for Rutland, VT July 2015.	35
Figure 22 Observed and modeled wind direction for Rutland, VT January 2015.	36
Figure 23 Observed and modeled wind direction for Rutland, VT July 2015.	36
Figure 24 Observed and modeled temperature for Martha’s Vineyard January 2015.	39

Figure 25	Observed and modeled temperature for Martha's Vineyard July 2015.	39
Figure 26	Observed and modeled temperature for Worcester January 2015.	40
Figure 27	Observed and modeled temperature for Worcester July 2015.	40
Figure 28	Observed and modeled temperature for Rutland, VT January 2015.	41
Figure 29	Observed and modeled temperature for Rutland, VT July 2015.	41
Figure 30	Observed and modeled humidity for Martha's Vineyard January 2015.	44
Figure 31	Observed and modeled humidity for Martha's Vineyard July 2015.	44
Figure 32	Observed and modeled humidity for Worcester January 2015.	45
Figure 33	Observed and modeled humidity for Worcester July 2015.	45
Figure 34	Observed and modeled humidity for Rutland, VT January 2015.	46
Figure 35	Observed and modeled humidity for Rutland, VT July 2015.	46

List of Tables

	<u>Page</u>
Table 1. Annual NO ₂ Impacts at Class I Areas	15
Table 2. Inland Surface Stations for the Statistical Analysis	19
Table 3. Coastal Surface Stations for the Statistical Analysis	20
Table 4. Overwater Stations for the Statistical Analysis	20
Table 5. Statistical Model Performance for Wind Speed and Direction	23
Table 6. Statistical Model Performance for Temperature	38
Table 7. Statistical Model Performance for Specific Humidity	43

Acronyms and Abbreviations

ARM2	Ambient Ratio Method Version 2
BART	Best Retrofit Available Technology
EPA	U.S. Environmental Protection Agency
FLAG	Federal Land Managers' Air Quality Related Values Work Group
FLM	Federal Land Managers
IOA	Index of Agreement
ISD	Integrated Surface Database
K	Kelvin
kg	kilogram
km	kilometers
LCC	Lambert Conformal Conic
m	meters
m/s	meters per second
NO _x	Nitrogen oxides
NO ₂	Nitrogen dioxide
NPS	National Park Service
NWR	National Wildlife Refuge
PSD	Prevention of Significant Deterioration
RMSE	Root Mean Square Error
SIL	Significant Impact Level
UTM	Universal Transverse Mercator
µg/m ³	Micrograms per cubic meter
WRF	Weather Research and Forecast Model

Limitations

This analysis makes use of the CALPUFF model to predict annual average NO₂ concentrations within three Class I areas. Modeling was performed using conservative assumptions with regard to chemistry and deposition.

Source emissions and other emission parameters were provided to Exponent, Inc. (Exponent) for use in this modeling study and no evaluation of these parameters was performed. The results presented in this report are based on the best information available at this time. If additional information becomes available, Exponent may update or otherwise revise or amend the findings in this report.

1 CALPUFF Class I Simulations

1.1 Purpose

Modeling has been conducted to assess annual average NO₂ concentrations within three Class I areas located in closest proximity to the Vineyard Wind project site. The three Class I areas evaluated include: Lye Brook Wilderness Area located in Vermont, Presidential Range – Dry River Wilderness located in New Hampshire and Brigantine Wilderness Area located in New Jersey. Emissions were quantified for various project construction sources associated with development of the Vineyard Wind project. The results of the modeling analysis were compared with the annual NO₂ Significant Impact Level (SIL) and the modeling was used to demonstrate that construction activities are not predicted to cause an exceedance of the annual NO₂ SIL.

1.2 Model Selection

Modeling has been conducted using the CALPUFF air dispersion model. CALPUFF is well suited for situations involving complex flows including spatial changes in meteorological fields due to factors such as the presence of complex terrain or the influence of water bodies, urbanization, plume fumigation (coastal fumigation or inversion break-up conditions), light wind speed or calm wind impacts, or other factors for which a steady-state-straight-line modeling approach is not appropriate. CALPUFF can account for the cumulative impacts of multiple spatially distributed sources within a large region and properly account for transport time and the potential for stagnation and recirculation.

CALPUFF is recommended for Class I area air quality impact assessments by the Federal Land Managers Workgroup (FLAG, 2010). CALPUFF is also recommended by the U.S. Environmental Protection Agency (EPA) as the preferred model for Best Retrofit Available Technology (BART) analyses (Federal Register, July 6, 2005).

1.3 Source Data

Emission parameters for sources included in the modeling were provided to Exponent by Epsilon Associates. The source inventory includes a total of 21,275 NO_x emission point sources. Stack parameters included stack location, exit height, diameter, exit velocity, exit temperature and NO_x emission rate. All sources were assumed to have a base elevation of zero meters above sea level and a vertical orientation.

1.4 Meteorological Data

Meteorological data was supplied by the Weather Research and Forecast Model (WRF). Three years of WRF simulations (2015-2017) converted into CALMET format using the MMIF processor were purchased from Lakes Environmental. A summary of the options and configuration used in running WRF is provided in Appendix A. MMIF allows prognostic model data to be reformatted directly into a CALPUFF ready format and by-pass the calculations performed by the CALMET model. MMIF was run to pass through meteorological data fields and to maintain the horizontal grid resolution of the parent WRF simulations. Default options were used for the calculation of stability class and mixing heights. In the vertical, ten CALMET layers were defined consistent with the default layers specified by EPA/FLM guidance (layer tops of 20, 40, 80, 160, 320, 640, 1200, 2000, 3000 and 4000 meters).

The original WRF simulation was provided in Lambert Conformal projection with an origin of 41.882 N, 72.465 W and standard parallels of 32 N and 51 N. The datum used in the WRF simulation was NWS-84 and the horizontal grid resolution was 4 km. These projections and the grid resolution were maintained by MMIF and further used in the CALPUFF simulations.

The meteorological data fields supplied by WRF have been evaluated to ensure they reliably represent conditions within the modeling domain. Section 2 of this report includes an evaluation of model performance for parameters including wind speed, wind direction, temperature and specific humidity. Comparisons are made with observed meteorological data within the modeling domain. The comparisons show that the WRF simulations provide a representative set of meteorological parameters which are important for air dispersion modeling.

1.5 Model Domain

A modeling domain has been defined to encompass the project site and the three identified Class I areas (Lye Brook, Brigantine and Presidential Range – Dry River). This domain is shown in Figure 1. A buffer of 50 km is maintained around each Class I area and the project site in order to allow for potential recirculation of pollutants. A 4 km grid resolution consistent with the WRF simulations was used in the CALPUFF modeling.

1.6 Class I Receptors

The Class I modeling used Class I area receptors obtained from the National Park Service (NPS) data stored at the following web site:

<https://irma.nps.gov/DataStore/Reference/Profile/2249830>. The 46 receptors for Brigantine Wilderness Area are shown in Figure 2, the 103 receptors for Lye Brook are shown in Figure 3 and the 188 receptors for Presidential Range – Dry River are shown in Figure 4.

The receptor locations were provided by NPS in latitude and longitude. These locations were converted to Lambert Conformal coordinates for use in CALPUFF consistent with the original WRF projection. Receptor heights provided in the downloaded receptor file were used in modeling.

1.7 CALPUFF Configuration

Modeling was conducted to calculate annual NO₂ concentrations. No chemical transformation of NO_x was performed in the modeling (MCHEM=0), which resulted in a conservative assessment of annual NO₂ concentrations. NO_x to NO₂ conversion was calculated using CALPOST with a table of conversion rates which vary by NO_x concentration. The binned conversion rates were set consistent with the values used in the AERMOD ARM2 method. Additionally, no deposition was calculated which results in further conservatism. For all other model options, CALPUFF was configured using settings consistent with USEPA Long Range Transport guidance.

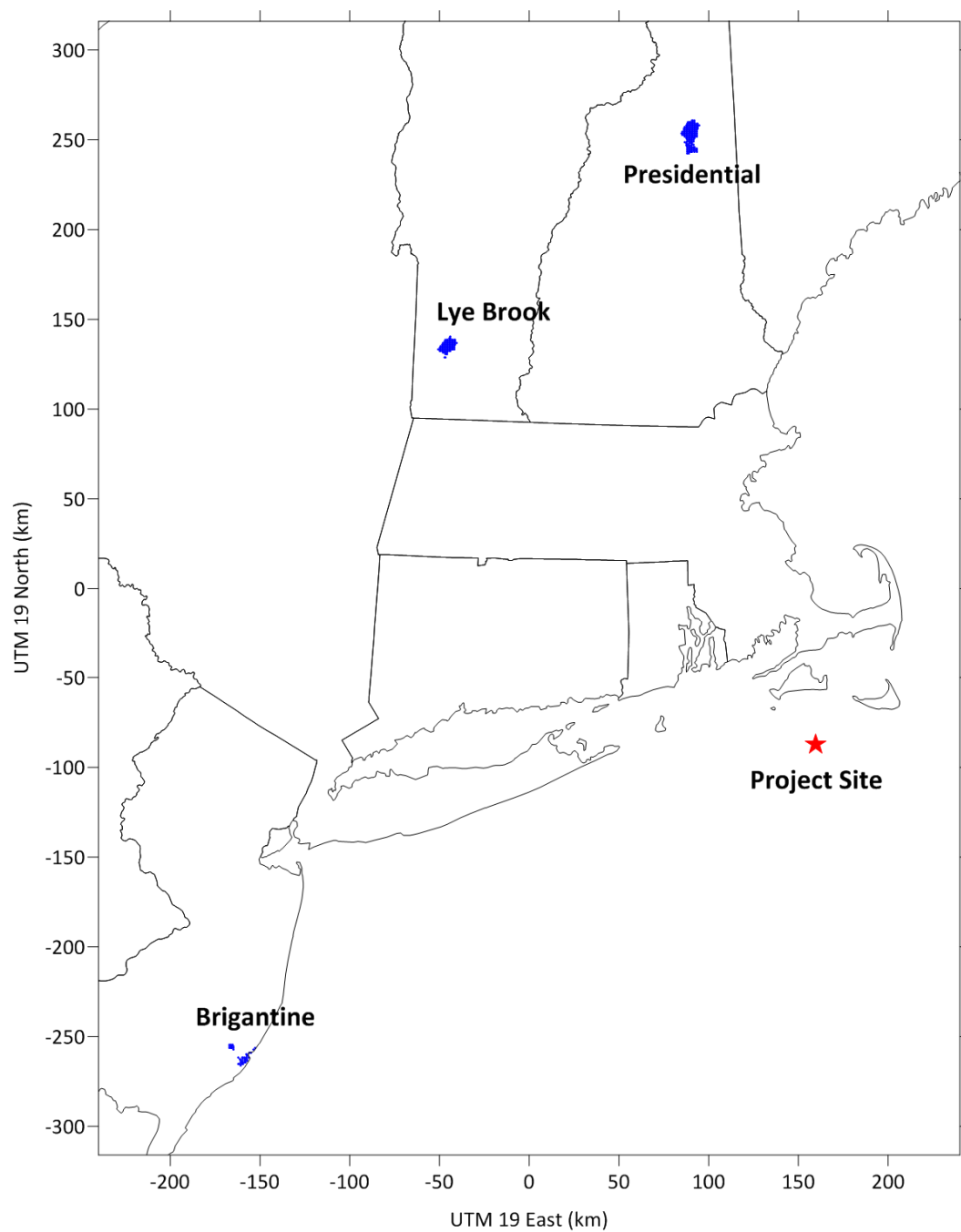


Figure 1 CALPUFF modeling domain and modeled Class I areas.

1808644.000 - 2691

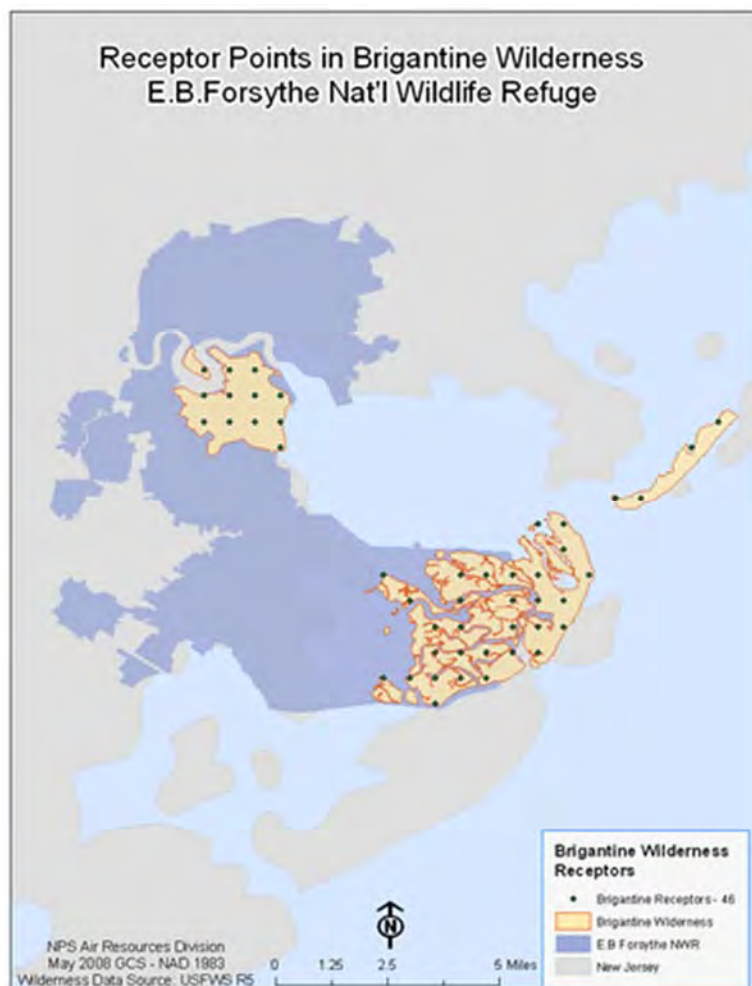


Figure 2 Class I Area Receptors for Brigantine Wilderness Area

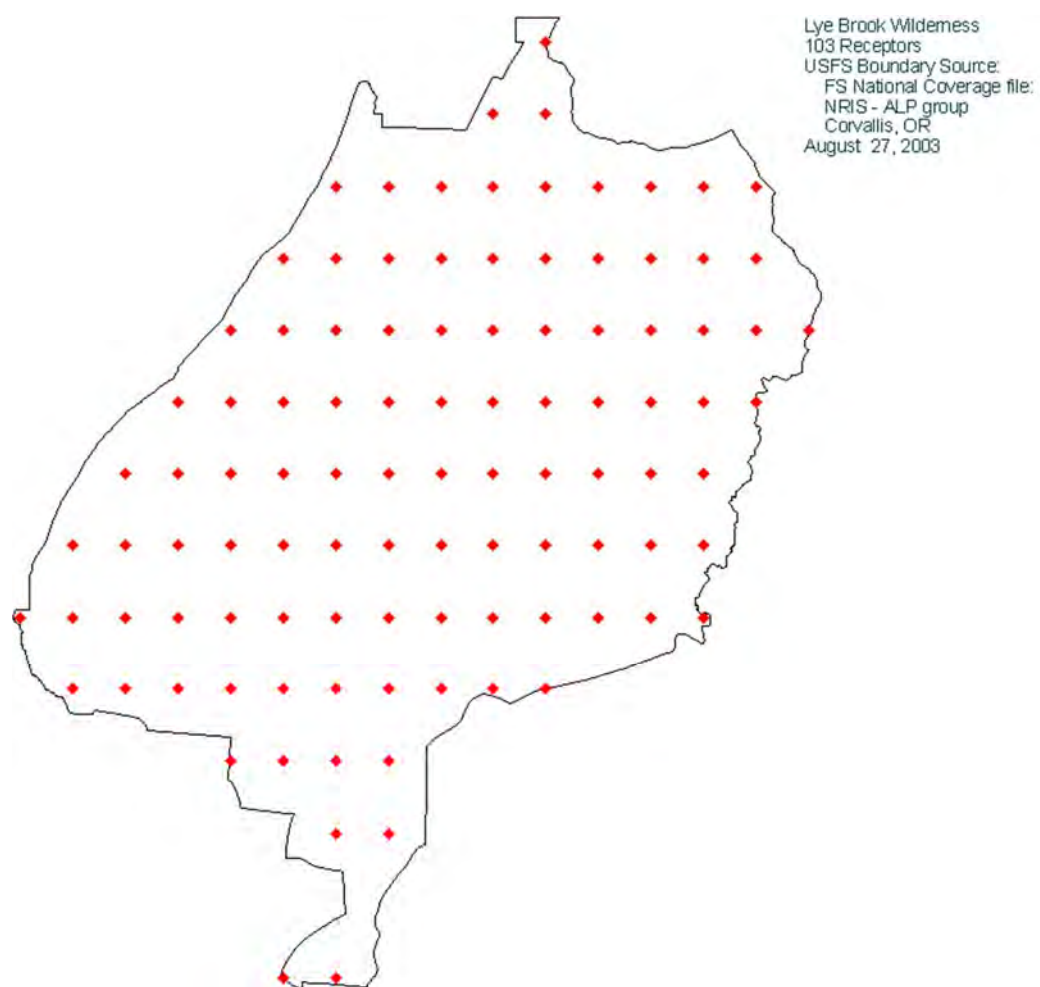


Figure 3 Class I Area Receptors for Lye Brook

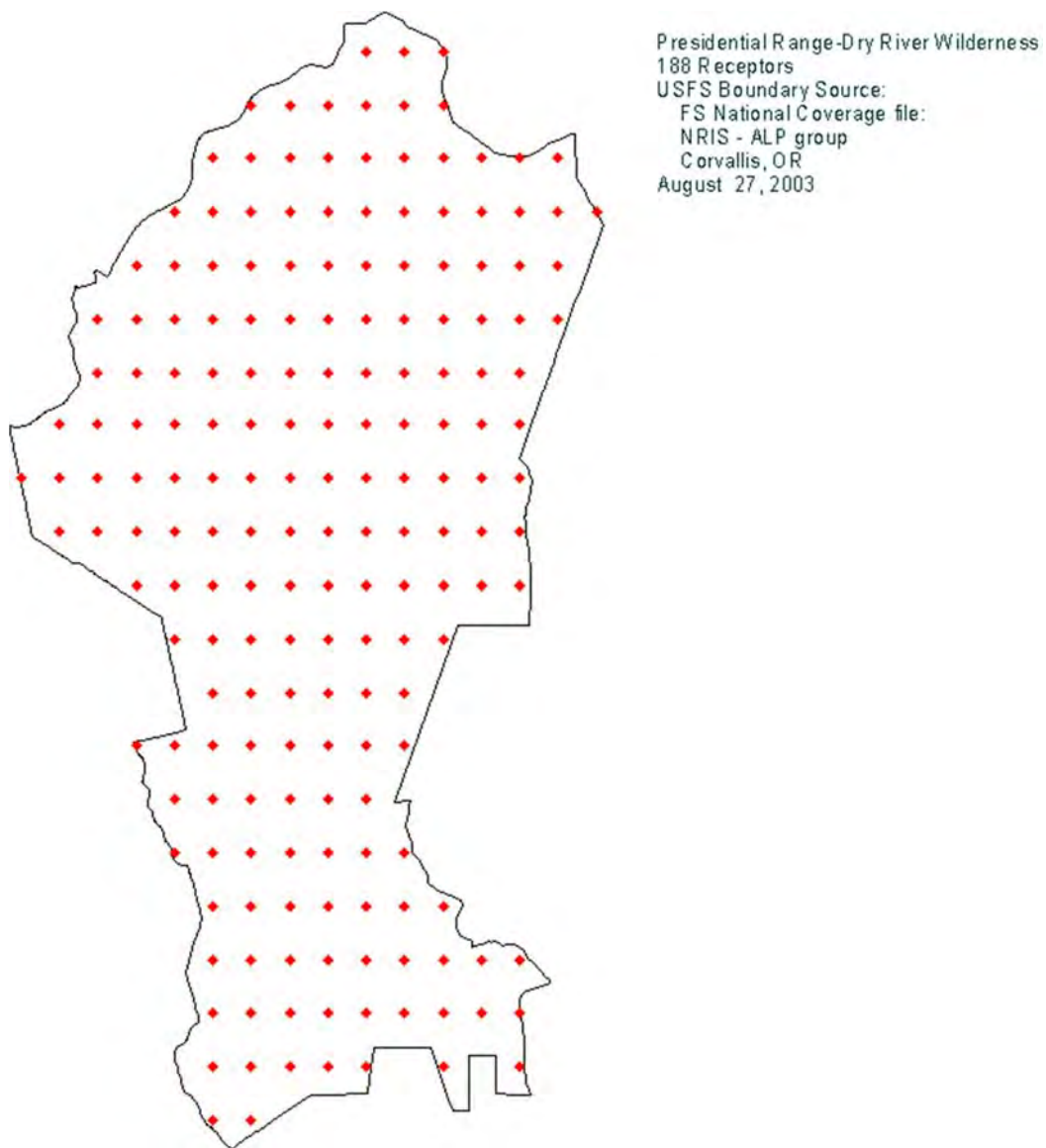


Figure 4 Class I Area Receptors for Presidential Range – Dry River

1.8 Annual NO₂ Project Impacts

Project NO_x emissions were modeled with CALPUFF and converted to NO₂ using CALPOST in order to determine annual NO₂ impacts in the three Class I areas. The predicted annual NO₂ impacts were compared to the corresponding annual Class I SIL for NO₂ (0.1 µg/m³). The comparison with the SIL was based on the maximum predicted annual impact in any of the three modeled years.

The maximum predicted annual NO₂ project impacts for each Class I area are summarized below in Table 1. All impacts are well below the corresponding Class I SIL for NO₂.

Therefore, the project will not cause or contribute to any violations of the annual NO₂ Class I PSD increment since its impacts are insignificant.

Table 1. Annual NO₂ Impacts at Class I Areas

Class I Area	2015	2016	2017	max
Brigantine Wilderness Area	0.005	0.009	0.006	0.009
Lye Brook Wilderness Area	0.003	0.003	0.004	0.004
Presidential Range –Dry River	0.004	0.004	0.005	0.005

2 WRF Performance Evaluation

2.1 Performance Criteria

In order to evaluate performance of the WRF prognostic model, modeled meteorological fields have been compared with observed data collected at stations within the modeling domain. This analysis includes the use of statistical criteria to evaluate model performance and applicability for use with air dispersion models. Model performance was evaluated using the statistical measures of agreement between observations and model simulated values based on the approach of Willmont (1981) and the benchmarks developed by Emery et al. (2001) and Tesche et al. (2001) for their mesoscale modeling studies. These are the same metrics and benchmarks included in the MMIFStat program and described in the accompanying User Guide (McNally 2010).

Four statistical measures were computed: Index of Agreement (IOA), Mean Bias, Root Mean Square Error (RMSE), and Gross Error. IOA is computed using the equations from the study of Willmont (1981):

$$IOA = 1 - \left[\frac{IJ.RMSE^2}{\sum_{j=1}^J \sum_{i=1}^I |P_j^i - M_o| + |O_j^i - M_o|} \right] \quad (2.1)$$

where RMSE is calculated using the equation

$$RMSE = \left[\frac{i}{IJ} \sum_{j=1}^J \sum_{i=1}^I (P_j^i - O_j^i)^2 \right]^{1/2} \quad (2.2)$$

P_j^i and O_j^i are the prediction and the observation at Station j and time i . M_o is the Mean Observation and equal to

$$M_o = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I O_j^i \quad (2.3)$$

The other two qualities used in the evaluation are Mean Bias (B) and Gross Error (E). Mean Bias is calculated using:

$$B = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I (P_j^i - O_j^i) \quad (2.4)$$

Gross Error equals:

$$E = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I |P_j^i - O_j^i| \quad (2.5)$$

Benchmarks using these statistical measures have been developed by Emery et al. (2001) and Tesche et al. (2001) for meteorological parameters including wind speed, direction, temperature and specific humidity. The benchmark values were developed based on an analysis of a collection of prognostic meteorological model runs available at the time. They are intended to represent typical performance for prognostic modeling simulations and serve as guidelines for good model performance.

The benchmarks should not be considered as strict pass/fail criteria and serve as part of a holistic evaluation of model performance. The analysis which follows includes other evaluations including comparisons of wind roses and evaluations of meteorological time series in order to assess time matched model performance and reproducibility of diurnal cycles.

2.2 Observed Meteorological Data

CALPUFF is a three dimensional air dispersion model that requires representative meteorological data for a full grid of points across the modeling domain. To evaluate the appropriateness of prognostic data for use with CALPUFF, evaluations should be conducted for representative locations throughout the domain.

For this evaluation, surface meteorological observations have been taken from the Integrated Surface Database (ISD) (<https://www.ncdc.noaa.gov/isd>). This database includes hourly observations for approximately 3,000 active stations across the United States. For this evaluation, stations within the modeling domain were identified from the ISD dataset. All stations with a 10 meter anemometer height were selected in order to allow for a direct comparison between the observations and the meteorological data included in the first layer of the MMIF generated CALMET data files. This resulted in a total of 49 stations. These stations have further been divided into two categories, coastal and inland, where coastal stations are those sites located within 15 km of the coastline. The stations included in the analysis are summarized in Table 2 (Inland) and Table 3 (Coastal) and shown in Figure 5.

To further evaluate WRF model performance at over-water locations, five stations were extracted from the National Data Buoy Center archive (www.ndbc.noaa.gov). These stations are summarized in Table 4 and are also shown in Figure 5. Because over-water data is not routinely collected at 10 meters, the wind data needed to be profiled to 10 meter height in order to perform a comparison with the 10 meter modeled layer. Wind speed was vertically profiled up or down using a log based boundary layer profile with a wind speed dependent calculation of roughness length as described by Hosker (1974). Since the roughness length calculation itself requires a measurement of 10 meter wind speed, an iterative approach was used.

Table 2. Inland Surface Stations for the Statistical Analysis

USAF	WBAN	STATION NAME	STATE	ICAO	LAT	LON	ELEV(M)
722247	54785	Somerset Airport	NJ	KSMQ	40.624	-74.669	32
724074	93780	South Jersey Regional Arpt	NJ	KVAY	39.941	-74.841	14.9
724075	13735	Millville Municipal Arpt	NJ	KMIV	39.366	-75.078	18.3
724077	54779	Aeroflex-Andover Airport	NJ	K12N	41.009	-74.736	176.8
725015	4789	Orange County Airport	NY	KMGJ	41.509	-74.265	111.3
725027	54788	Meriden Markham Muni Arpt	CT	KMMK	41.51	-72.828	31.4
725029	64707	Waterbury-Oxford Airport	CT	KOXC	41.483	-73.133	221.3
725059	14702	Laurence G Hanscom Fld Apt	MA	KBED	42.47	-71.289	40.5
725068	54777	Taunton Municipal Airport	MA	KTAN	41.876	-71.021	13.1
725075	54768	Harriman-and-West Airport	MA	KAQW	42.697	-73.17	195.1
725080	14740	Bradley International Airport	CT	KBDL	41.938	-72.682	53.3
725085	54756	Orange Municipal Airport	MA	KORE	42.57	-72.291	169.2
725087	14752	Hartford-Brainard Airport	CT	KHFD	41.736	-72.651	5.8
725100	94746	Worcester Regional Airport	MA	KORH	42.271	-71.873	304.8
725107	4780	Fitchburg Municipal Arp	MA	KFIT	42.552	-71.756	106.1
725145	54746	Sullivan County Intl Arpt	NY	KMSV	41.701	-74.795	427.6
725165	94737	Rutland State Airport	VT	KRUT	43.533	-72.95	239
725180	14735	Albany International Airport	NY	KALB	42.747	-73.799	85.3
725220	14750	Floyd Bennett Memo Airport	NY	KGFL	43.338	-73.61	97.8
726116	94765	Lebanon Municipal Airport	NH	KLEB	43.626	-72.305	182.3
726140	54742	St. Johnsbury(Amos)	VT	K1V4	44.42	-72.019	212.4
726155	54736	Laconia Municipal Airport	NH	KLCI	43.567	-71.433	166.1
726160	94700	Berlin Municipal Airport	NH	KBML	44.576	-71.179	353
726163	54770	Jaffrey Mini-Slvr Rnch Apt	NH	KAFN	42.805	-72.004	317
726166	54781	W. H. Morse State Airport	VT	KDDH	42.891	-73.247	251.8
726183	54772	Eastern Slopes Rgnl Arpt	ME	KIZG	43.991	-70.948	135.6
726184	94709	Auburn/Lewiston Muni Arpt	ME	KLEW	44.05	-70.283	87.8
740001	54793	Sussex Airport	NJ	KFWN	41.199	-74.626	125
743945	14710	Manchester Airport	NH	KMHT	42.933	-71.436	67.4
744104	14763	Pittsfield Municipal Arpt	MA	KPSF	42.427	-73.289	363.9
744904	94723	Lawrence Municipal Airport	MA	KLWM	42.717	-71.124	45.4
744915	14775	Barnes Municipal Airport	MA	KBAF	42.158	-72.716	82.6

Table 3. Coastal Surface Stations for the Statistical Analysis

USAF	WBAN	STATION NAME	STATE	ICAO	LAT	LON	ELEV(M)
725016	54790	Brookhaven Airport	NY	KHWV	40.822	-72.869	25
725020	14734	Newark Liberty International Ap	NJ	KEWR	40.683	-74.169	2.1
725030	14732	La Guardia Airport	NY	KLGA	40.779	-73.88	3.4
725037	94745	Westchester County Airport	NY	KHPN	41.067	-73.708	115.5
725046	14707	Groton-New London Airport	CT	KGON	41.328	-72.049	3.1
725058	94793	Block Island State Airport	RI	KBID	41.168	-71.578	32
725060	14756	Nantucket Memorial Airport	MA	KACK	41.253	-70.061	14.6
725064	54769	Plymouth Municipal Airport	MA	KPYM	41.91	-70.729	45.4
725066	94724	Martha's Vineyard Airport	MA	KMVY	41.393	-70.615	20.7
725069	94624	Chatham Municipal Airport	MA	KCQX	41.688	-69.993	20.7
725070	14765	Theodore F Green State Airport	RI	KPVD	41.723	-71.433	16.8
725073	64708	Provincetown Muni Airport	MA	KPVC	42.072	-70.221	2.4
725088	54733	Beverly Municipal Airport	MA	KBVY	42.584	-70.918	32.9
727135	94623	Wiscasset Airport	ME	KIWI	43.964	-69.712	20.7
744860	94789	John F Kennedy Int.Airport	NY	KJFK	40.639	-73.762	3.4
744864	54787	Republic Airport	NY	KFRG	40.734	-73.417	24.7
744865	14719	Francis S Gabreski Ap	NY	KFOK	40.844	-72.632	20.4

Table 4. Overwater Stations for the Statistical Analysis

ID	Type	Anem Ht.	Lat	Lon
BUZM3	C-MAN	24.8	41.397	-71.033
44020	NDBC	4	41.493	-70.279
44017	NDBC	5	40.693	-72.049
44018	NDBC	5	42.206	-70.143
44025	NDBC	5	40.251	-73.164

2.3 Model Performance

2.3.1 Wind Speed and Direction

The results of the statistical assessment for wind speed and direction are presented in Table 5. Evaluation across all 49 surface stations (both coastal and inland) shows mean values which fall within the associated benchmarks. The bias for wind speed is positive which indicates WRF generated wind speeds that are slightly higher than observed. Bias for wind direction is small, which indicates that the distribution of wind directions seen over the year should provide a reliable representation of actual conditions.

Inland stations show slightly higher gross error in wind direction as compared with coastal locations. This may be attributable to greater terrain influences on inland locations which are not completely resolved by the 4 km WRF grid cells. Again, bias values are low for both subgroups indicating that the annual distribution of wind speeds and directions should be representative.

The overwater analysis is based on five identified buoy stations in the region around the project site. These stations show a higher wind direction bias and gross error which are near or slightly above the benchmark values. Wind speed RMSE is also slightly above the benchmark. The measurement height at these stations and the need to profile wind speed contributes to higher uncertainty for the observed values.

Figure 6 through Figure 11 show modeled and observed wind roses for 9 stations across the modeling domain. Separate comparisons are provided for each modeled year (2015-2017). The predominant wind directions are well correlated between the two datasets. Coastal sites, both on land and overwater, show a predominant northeast and southwest flow which is apparent in both the observation and the WRF dataset. For inland stations, individual peaks, such as the more prominent westerly sector at Worcester, may not exactly match or may be slightly rotated but the predominant wind directions are well captured. The overwater stations show higher wind speeds than the surface stations. This is the case for both the modeled and observed datasets.

Table 5. Statistical Model Performance for Wind Speed and Direction

		Wind Speed			Wind Direction	
	Year	IOA -	Mean Bias m/s	RMSE m/s	Mean Bias deg	Gross Error deg
Benchmark		≥ 0.6	$\leq \pm 0.5$	≤ 2	$\leq \pm 10$	≤ 30
All Surface	2015	0.73	0.36	2.02	2.60	25.32
	2016	0.73	0.31	2.02	2.54	26.03
	2017	0.72	0.36	2.03	3.50	25.75
Coastal Surface	2015	0.71	0.31	2.05	3.28	21.21
	2016	0.70	0.24	2.07	3.04	21.84
	2017	0.69	0.29	2.10	3.81	21.85
Inland Surface	2015	0.68	0.39	2.00	2.09	28.76
	2016	0.67	0.35	1.99	2.26	29.45
	2017	0.68	0.39	1.98	3.28	29.08
Overwater	2015	0.55	0.18	2.64	11.36	34.07
	2016	0.56	0.19	2.87	10.40	34.28
	2017	0.54	0.23	2.74	7.40	32.33

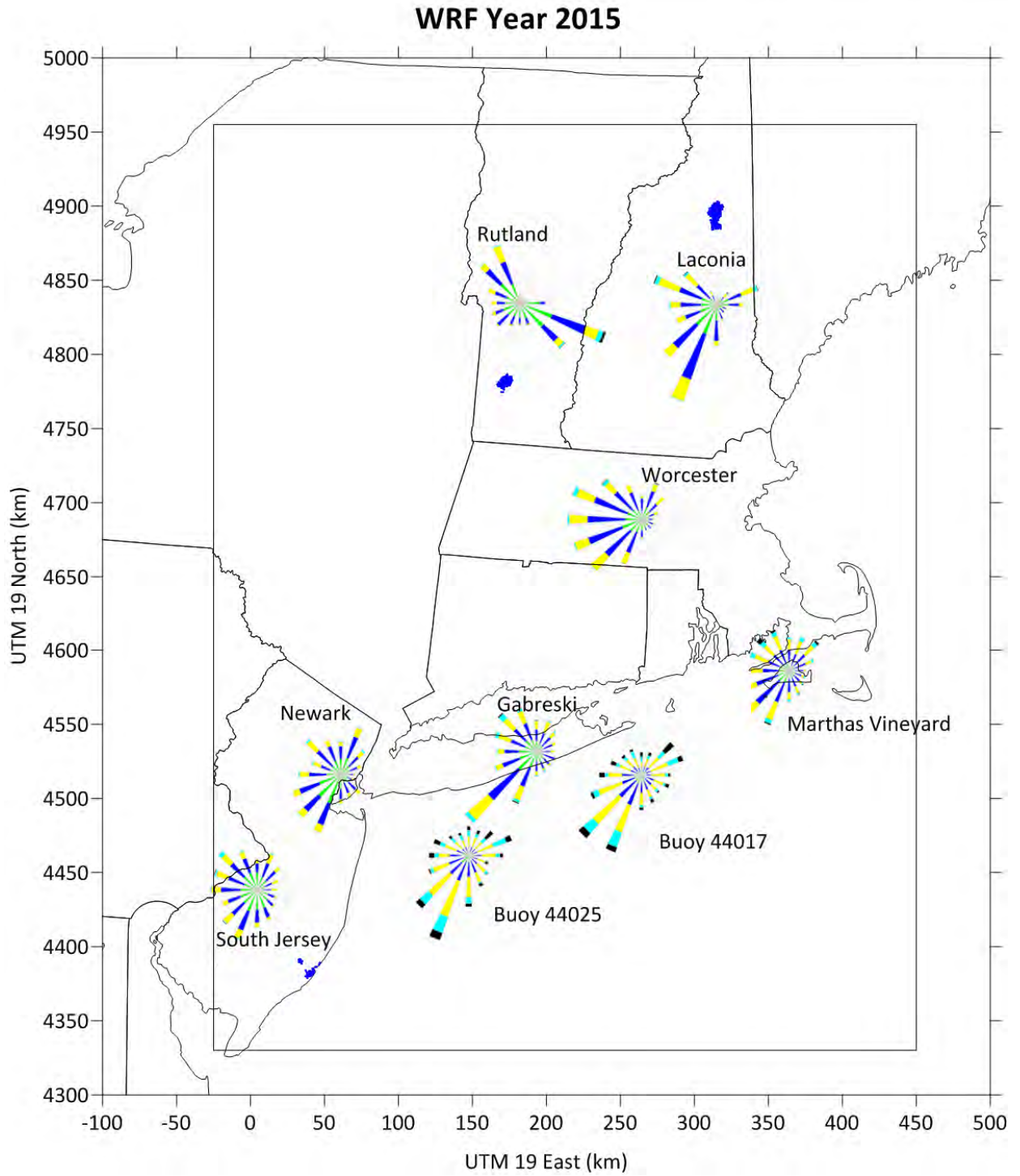


Figure 6 WRF predicted wind fields for year 2015

1808644.000 - 2691

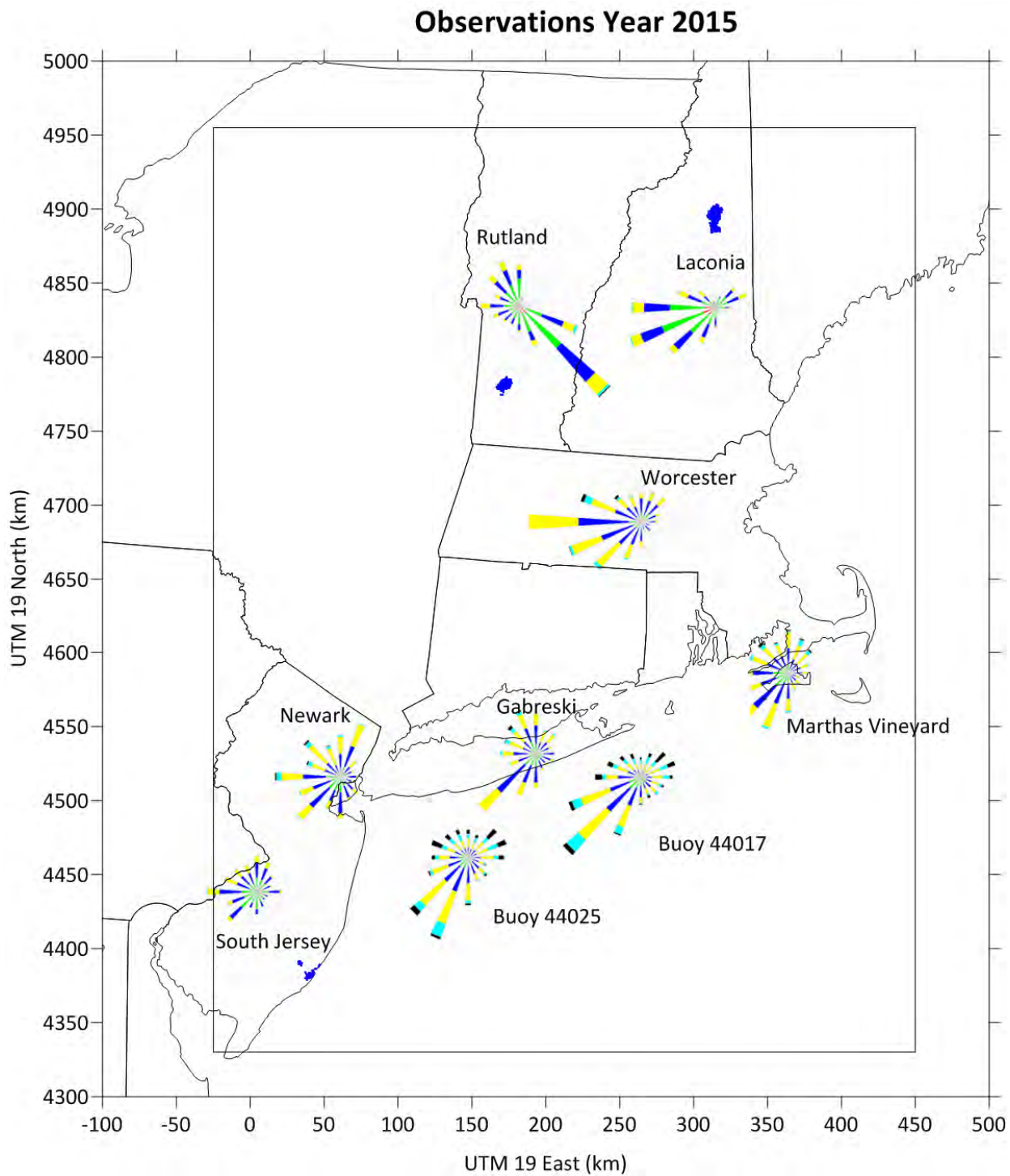


Figure 7 Observed wind fields for year 2015

1808644.000 - 2691

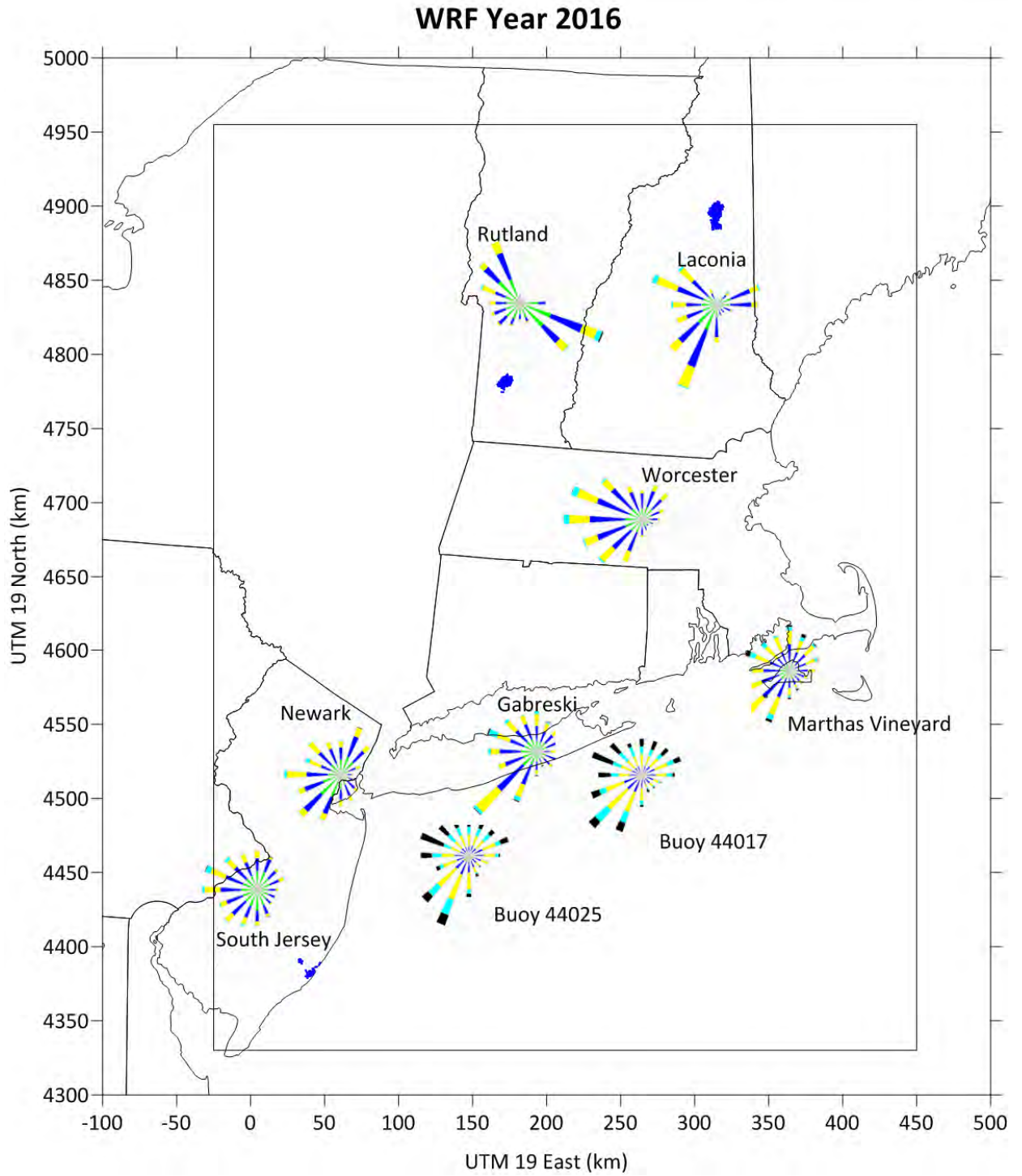


Figure 8 WRF predicted wind fields for year 2016

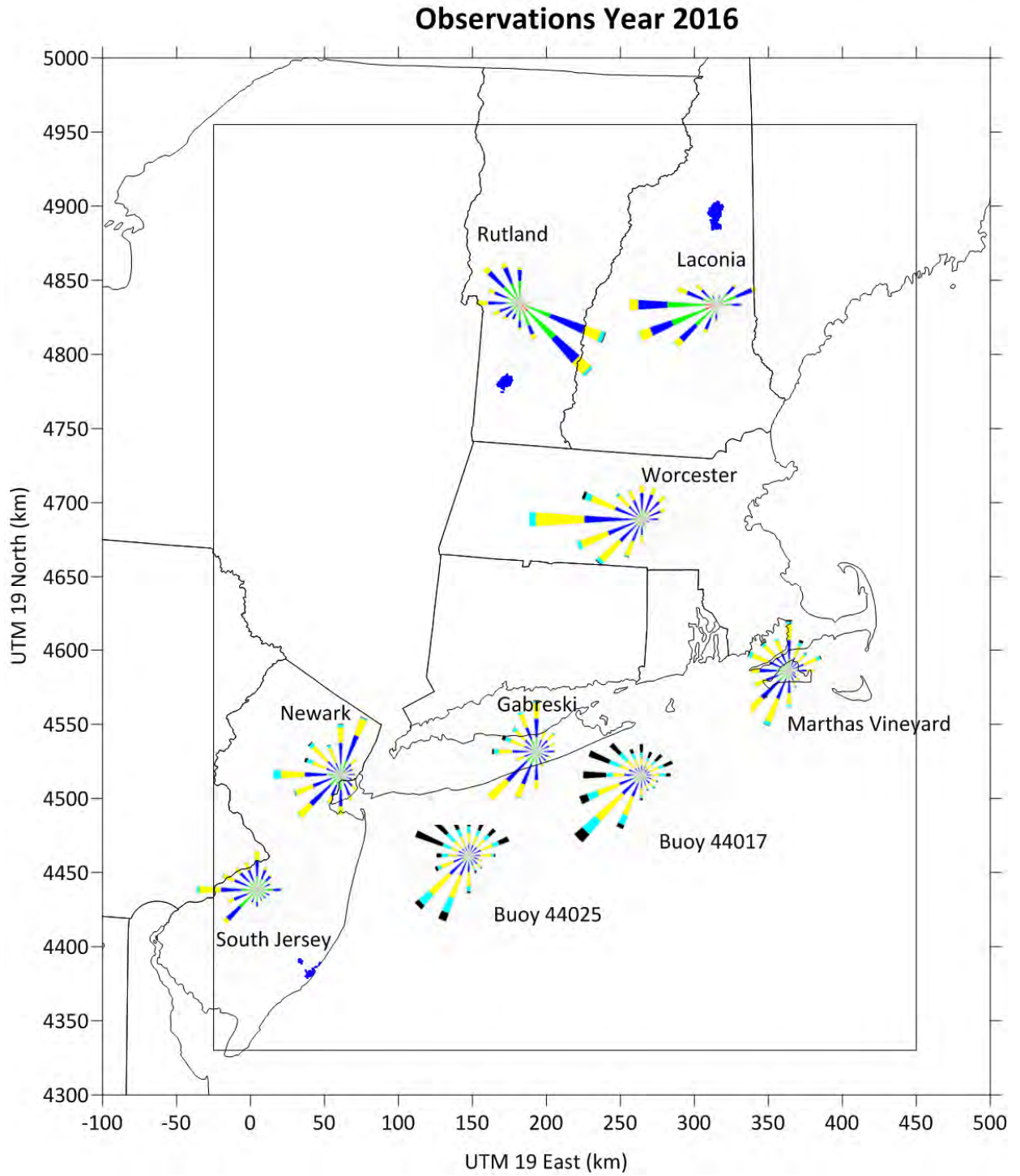


Figure 9 Observed wind fields for year 2016

1808644.000 - 2691

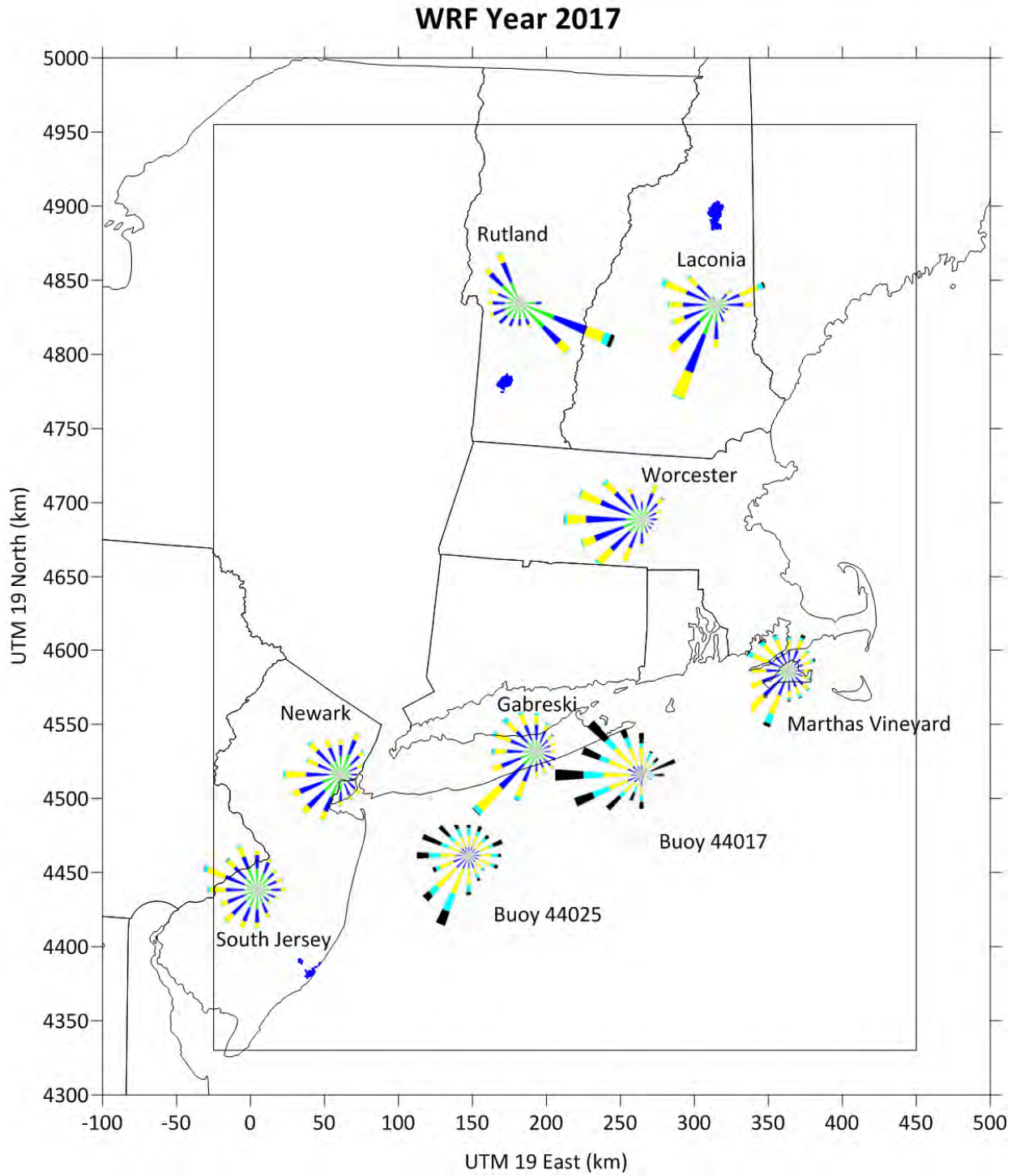


Figure 10 WRF predicted wind fields for year 2017

1808644.000 - 2691

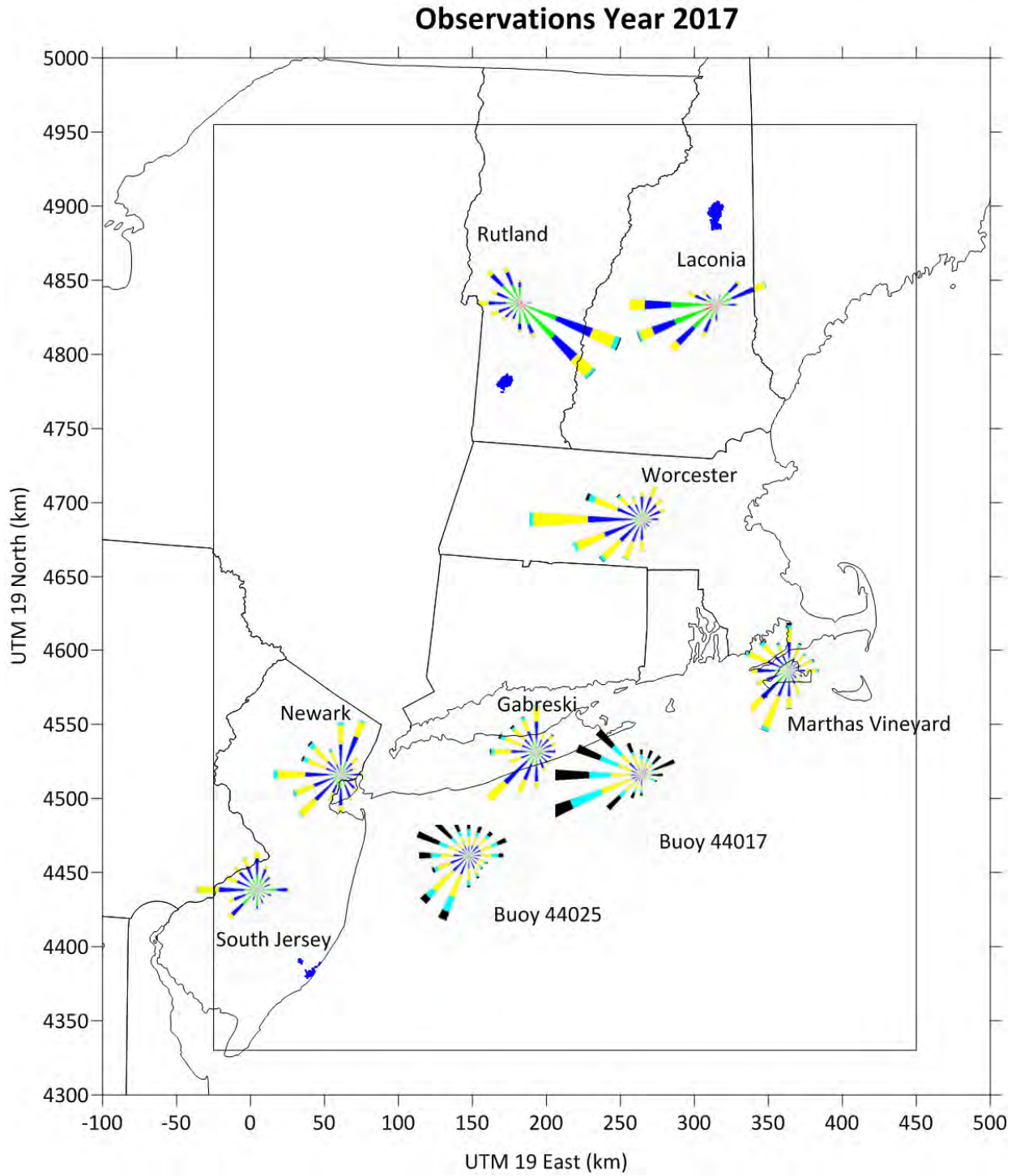


Figure 11 Observed wind fields for year 2017

1808644.000 - 2691

Some locations, such as the South Jersey station, show a large fraction of calm winds in the observed database. This is partially due to the 3 knot minimum wind speed recorded for these ASOS stations in the ISD database. The WRF generated winds show a greater fraction of non-calm hours for these stations with light winds. The light winds (less than 3 knots, but larger than 0 knots) in the WRF data set correspond to calm observed winds at these stations.

A more refined analysis is conducted using time series profiles to better quantify the time history of wind speeds and directions and also to examine diurnal profiles found in the two datasets in both winter (January) and summer (July). For this analysis, 3 stations were selected which spanned the distance from the project site to the Class I areas: Martha's Vineyard, Worcester and Rutland VT. Martha's Vineyard is located very close to the project site, while Rutland VT is located in a region and at a distance similar to the closest two Class I areas. Worcester represents regions in between, which would be transited by pollutants transported from the project site.

Figure 12 and Figure 13 show modeled and observed wind speeds for the months of January and July 2015 at Martha's Vineyard. The peak winds are well represented in the WRF dataset for both periods. Observed wind speeds that drop to zero indicate calm records in the ISD database and typically are matched with light winds in the WRF simulations. During the summer months, these light winds are most common at nighttime and early morning hours. Figure 14 and Figure 15 show the corresponding comparison for wind direction. The wind directions match well during both periods. Note that some records of zero for the observed wind direction represent hours of calm winds.

Figure 16 through Figure 23 show the same analysis for Worcester and Rutland, VT. At these inland stations, there are more frequent calm wind records in the observational database, which are generally well paired with WRF wind speeds of 2 m/s or less. At these stations, WRF under predicts some of the peak wind speeds and over predicts some light winds. The inland stations show a greater degree of wind direction variability which is reasonably well matched by WRF. The higher frequency of calm winds at Rutland, VT results in many hours with zero wind direction. During non-calm hours the observed wind directions are matched well by WRF.

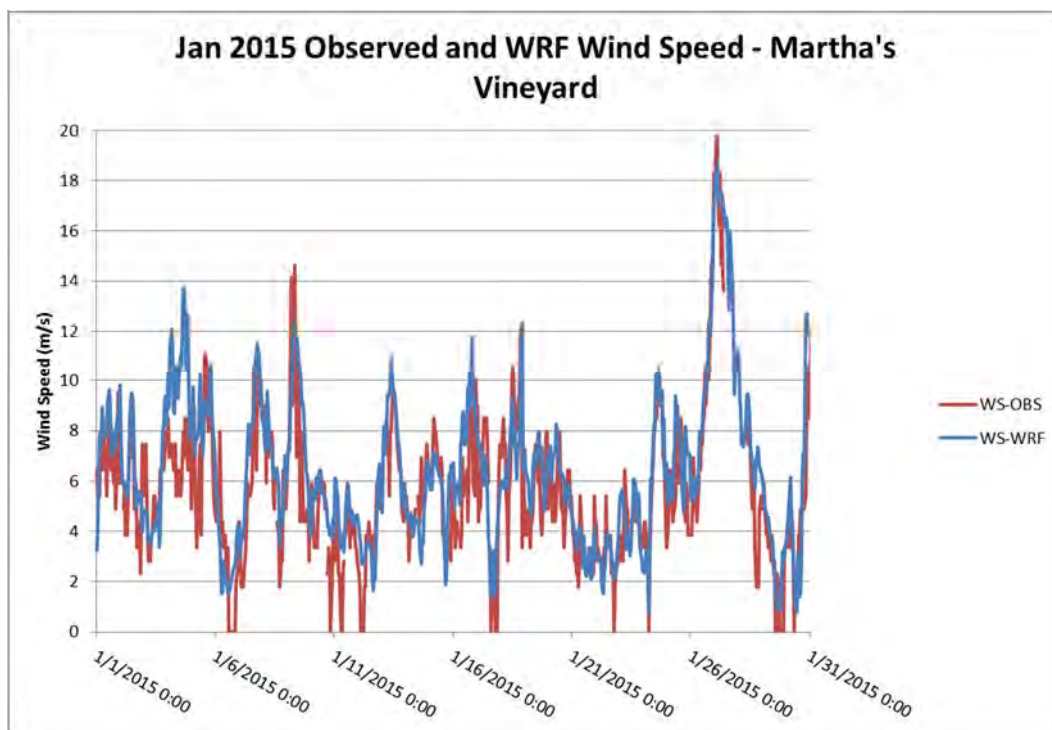


Figure 12 Observed and modeled wind speeds for Martha's Vineyard January 2015.

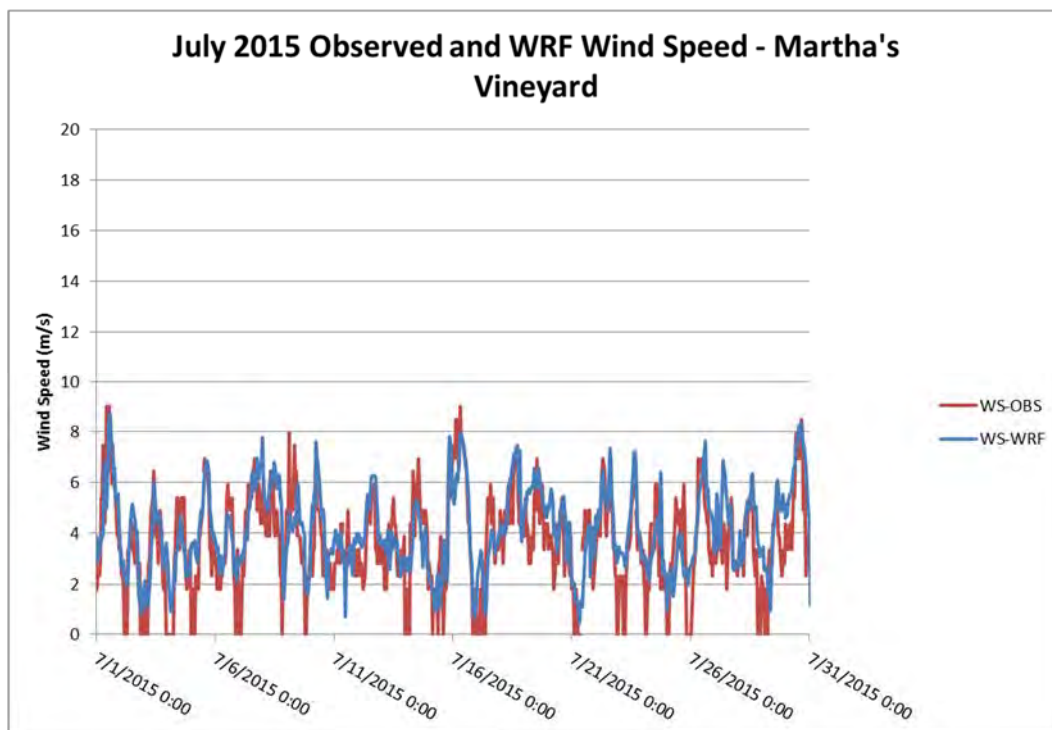


Figure 13 Observed and modeled wind speeds for Martha's Vineyard July 2015.

1808644.000 - 2691

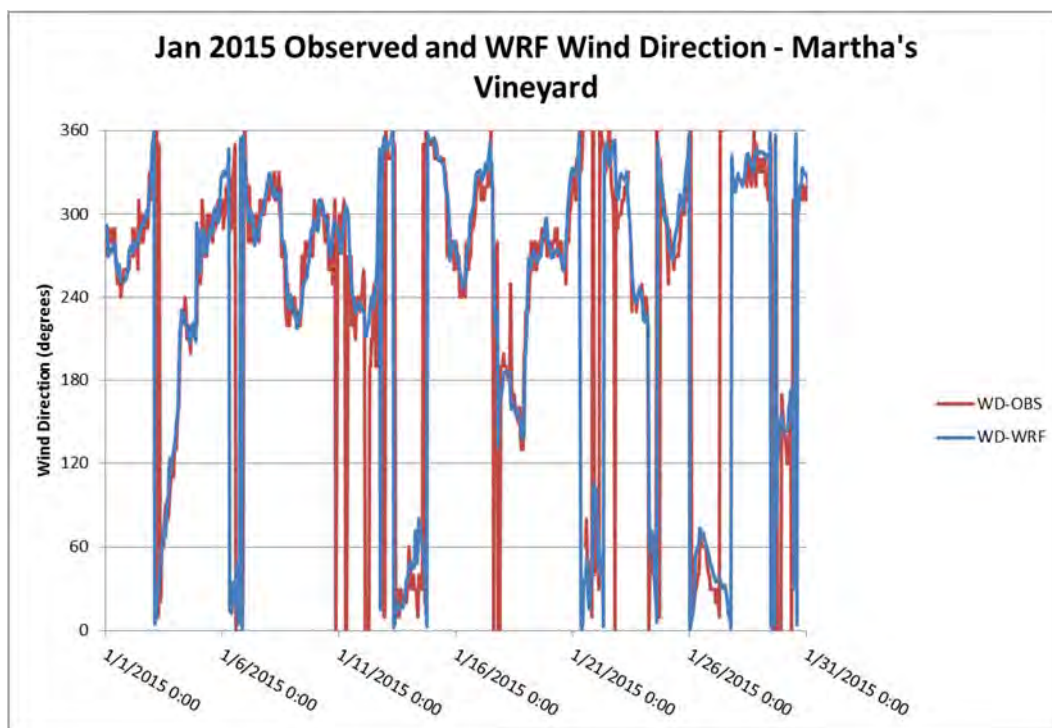


Figure 14 Observed and modeled wind direction for Martha's Vineyard January 2015.

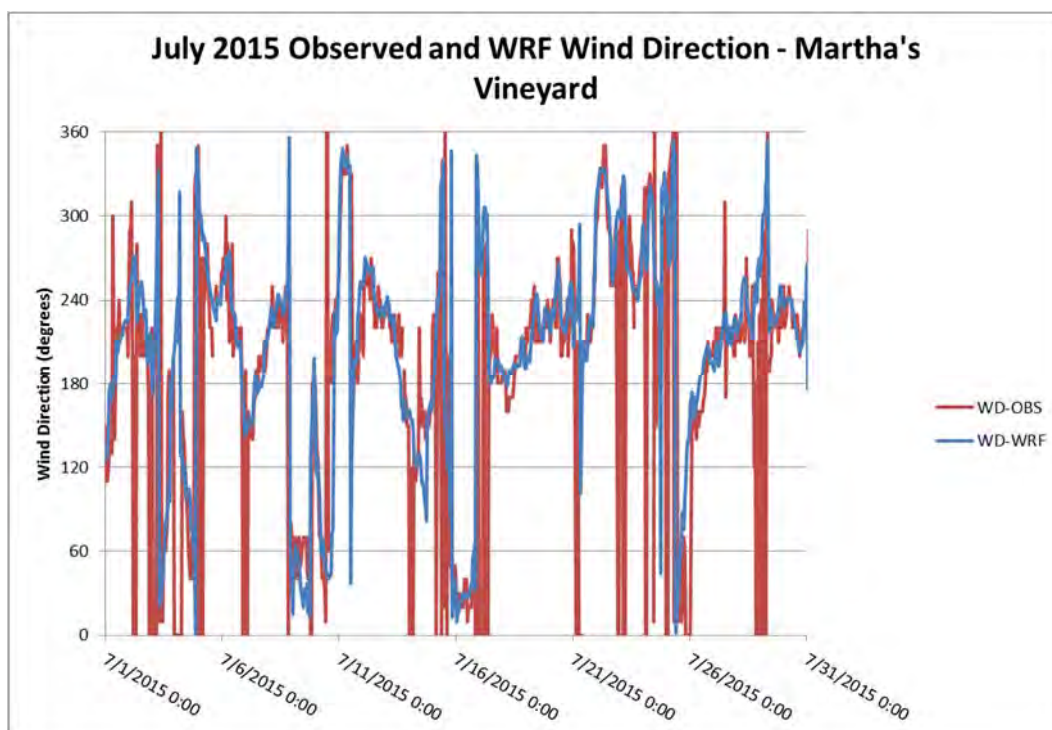


Figure 15 Observed and modeled wind direction for Martha's Vineyard July 2015.

1808644.000 - 2691

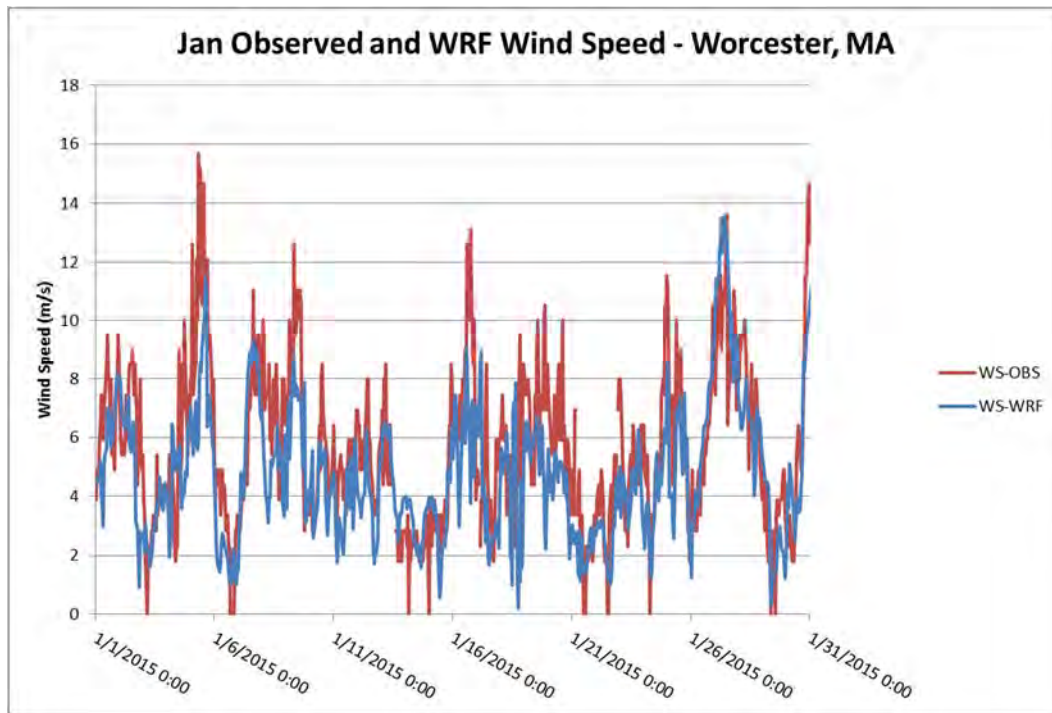


Figure 16 Observed and modeled wind speeds for Worcester January 2015.

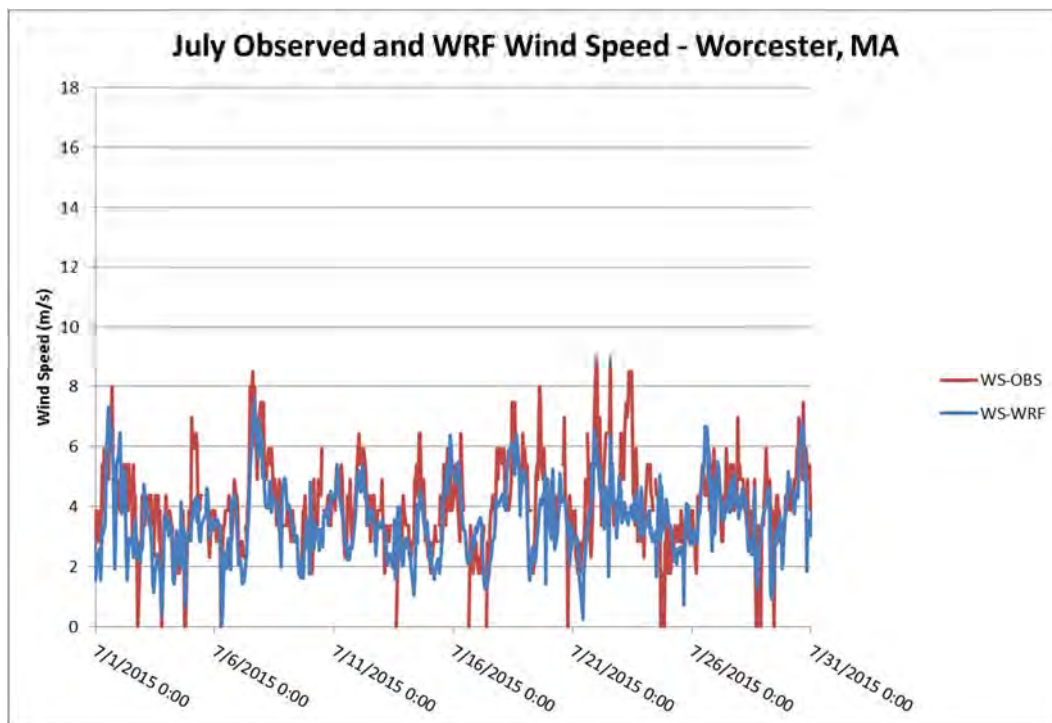


Figure 17 Observed and modeled wind speeds for Worcester July 2015.

1808644.000 - 2691

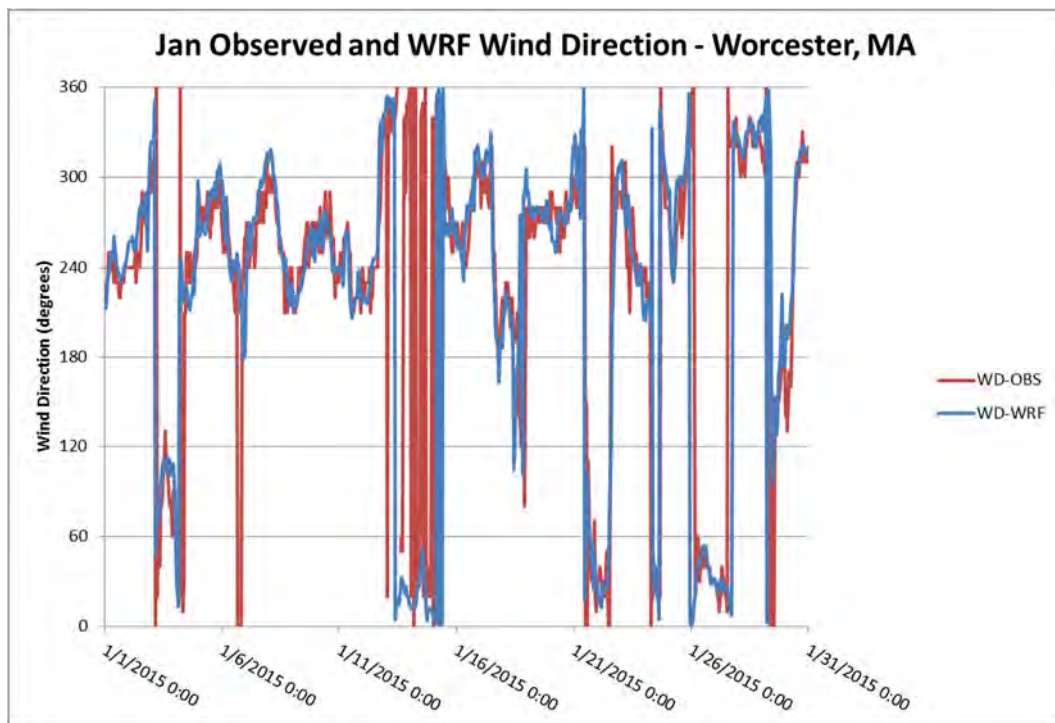


Figure 18 Observed and modeled wind direction for Worcester January 2015.

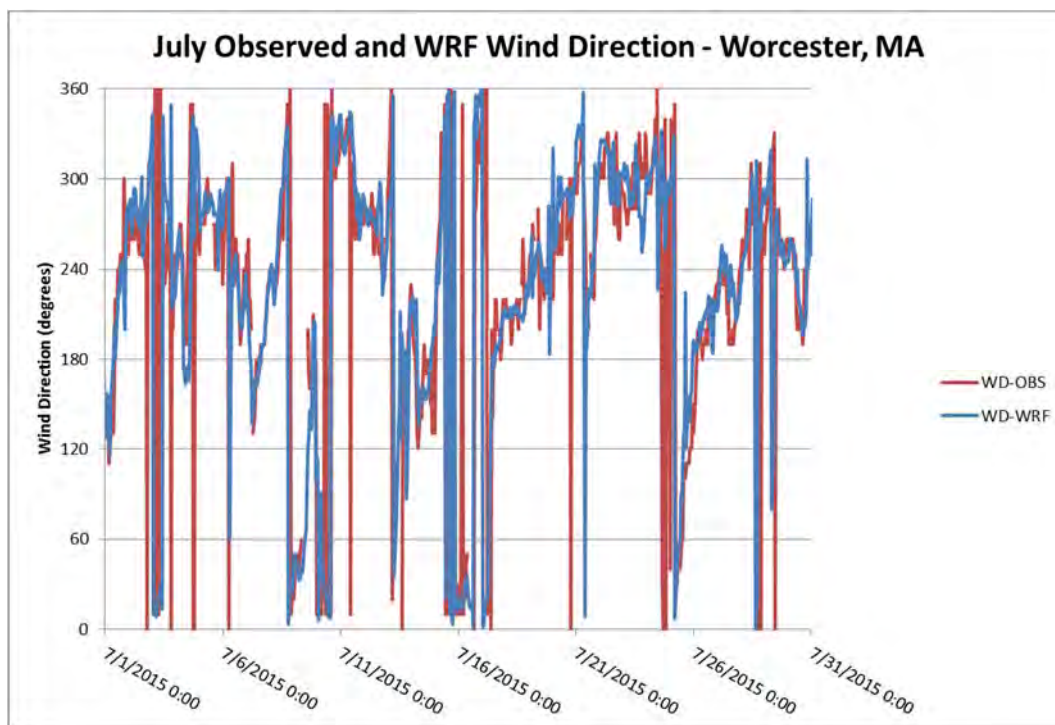


Figure 19 Observed and modeled wind direction for Worcester July 2015.

1808644.000 - 2691

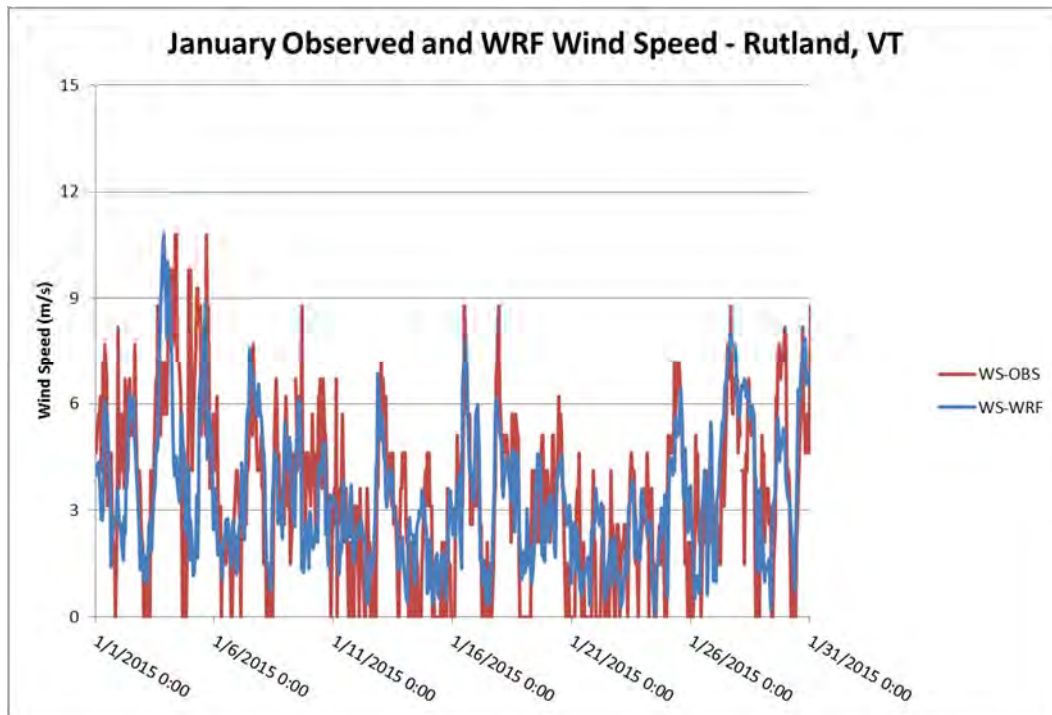


Figure 20 Observed and modeled wind speeds for Rutland, VT January 2015.

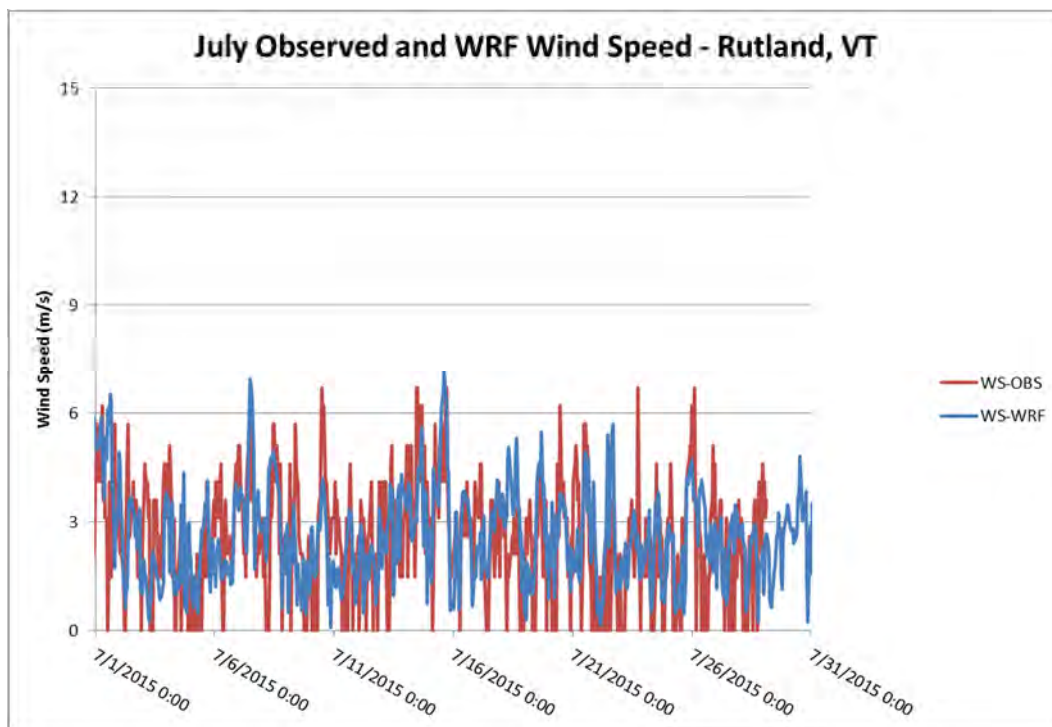


Figure 21 Observed and modeled wind speeds for Rutland, VT July 2015.

1808644.000 - 2691

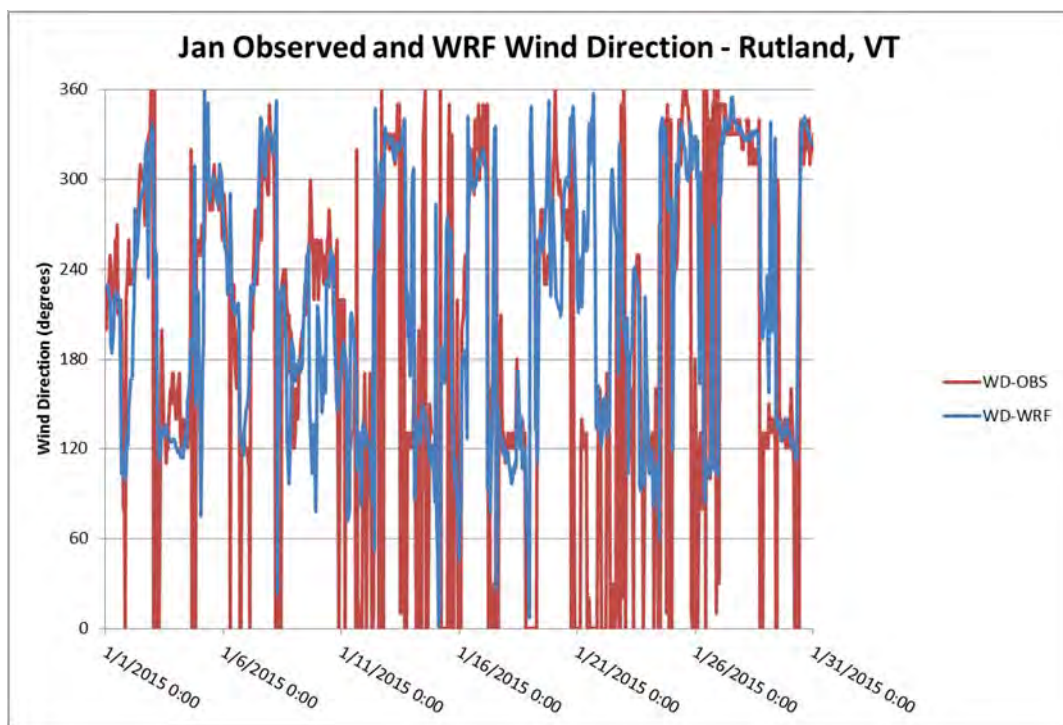


Figure 22 Observed and modeled wind direction for Rutland, VT January 2015.

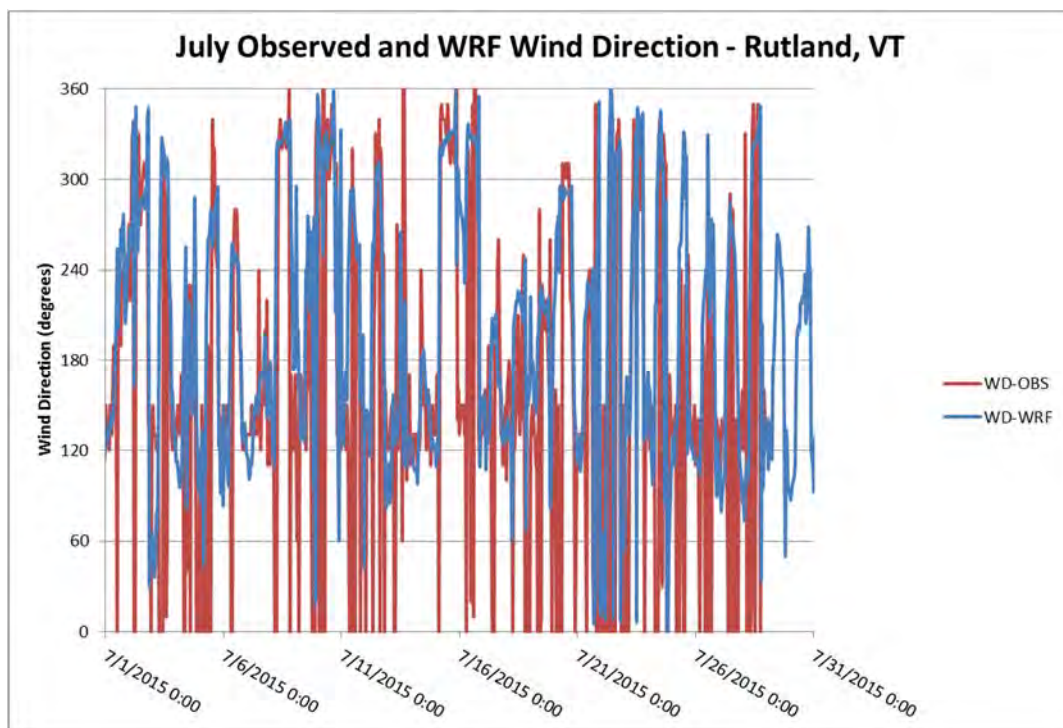


Figure 23 Observed and modeled wind direction for Rutland, VT July 2015.

1808644.000 - 2691

2.3.2 Temperature

A summary of the evaluation statistics for temperature are presented in Table 6. Bias values are low across all subgroups, which indicate no tendency to over or under predict temperatures. Gross errors are all within the benchmarks. The over water stations show an IOA which falls below the benchmark. This contrasts with otherwise good performance for bias and gross error at these stations.

Figure 24 and Figure 25 show time series of temperature for January and July 2015 at Martha's Vineyard. During the winter months, the temperature variation is well captured. Summer months show a more regular diurnal profile. The WRF model has a tendency to under predict the daytime high and over predict the nighttime low. This may be partially related to the 4 km grid size of the model. While this station is located over land, the model will include a certain amount of overwater land use in the grid cell. The water land use included in the grid cell may tend to modulate the modeled temperature swings.

Figure 26 through Figure 29 show the time series of temperature for January and July 2015 at Worcester and Rutland VT. The winter month performance is similarly well captured as at Martha's Vineyard. In July at Worcester, the diurnal profile of temperatures is well captured. However at Rutland, VT, the model accurately predicts the daytime high, but sometimes slightly over predicts nighttime low temperatures.

Table 6. Statistical Model Performance for Temperature

		Temperature		
	Year	IOA -	Mean Bias K	Gross Error K
Benchmark		≥ 0.8	$\leq \pm 0.5$	≤ 2
All Surface	2015	0.91	-0.15	1.83
	2016	0.91	-0.08	1.74
	2017	0.91	0.00	1.70
Coastal Surface	2015	0.88	-0.26	1.59
	2016	0.88	-0.19	1.51
	2017	0.88	-0.14	1.49
Inland Surface	2015	0.90	-0.09	1.96
	2016	0.90	-0.03	1.86
	2017	0.90	0.07	1.82
Overwater	2015	0.71	0.04	1.27
	2016	0.71	0.03	1.28
	2017	0.69	0.20	1.26

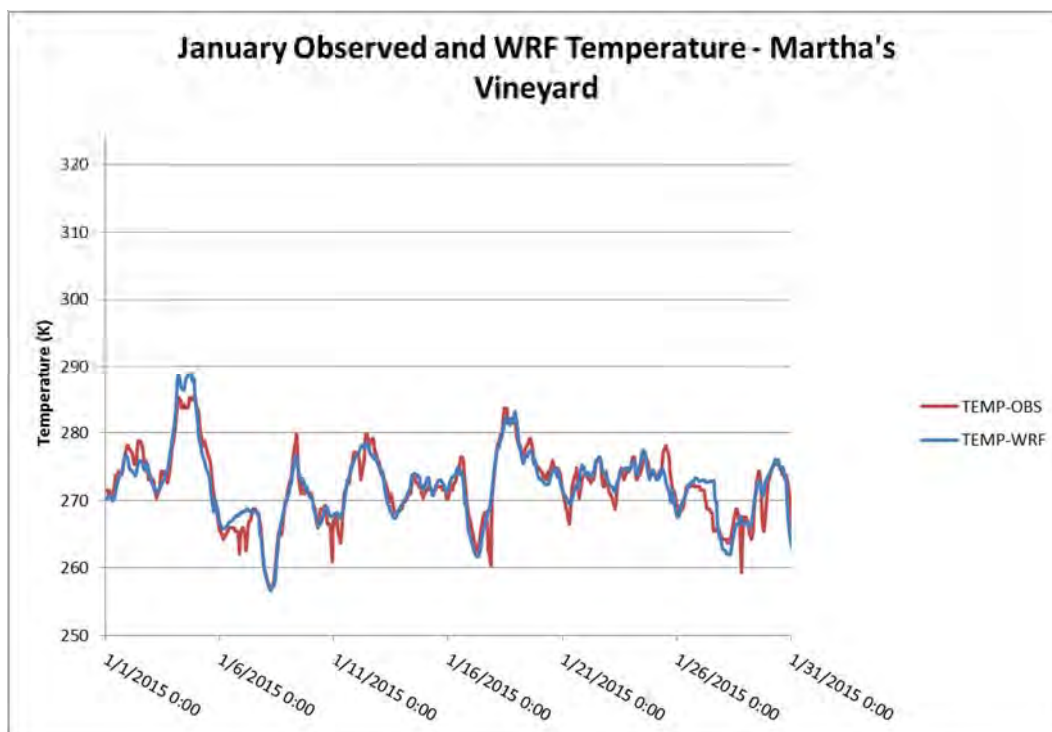


Figure 24 Observed and modeled temperature for Martha's Vineyard January 2015.

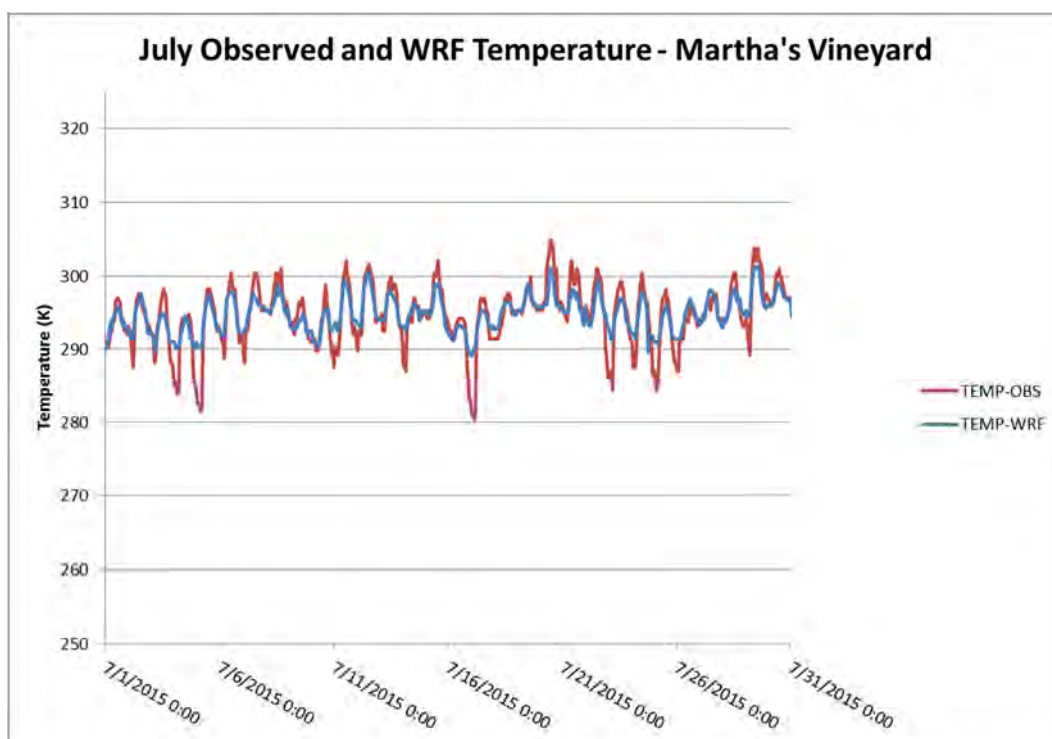


Figure 25 Observed and modeled temperature for Martha's Vineyard July 2015.

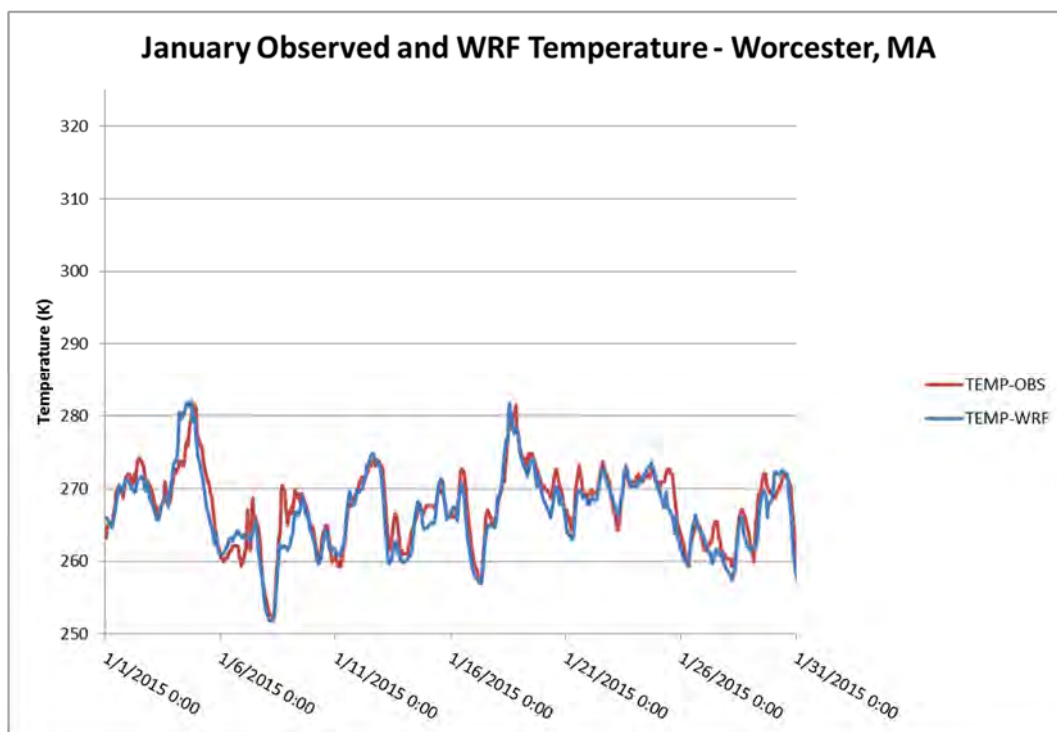


Figure 26 Observed and modeled temperature for Worcester January 2015.

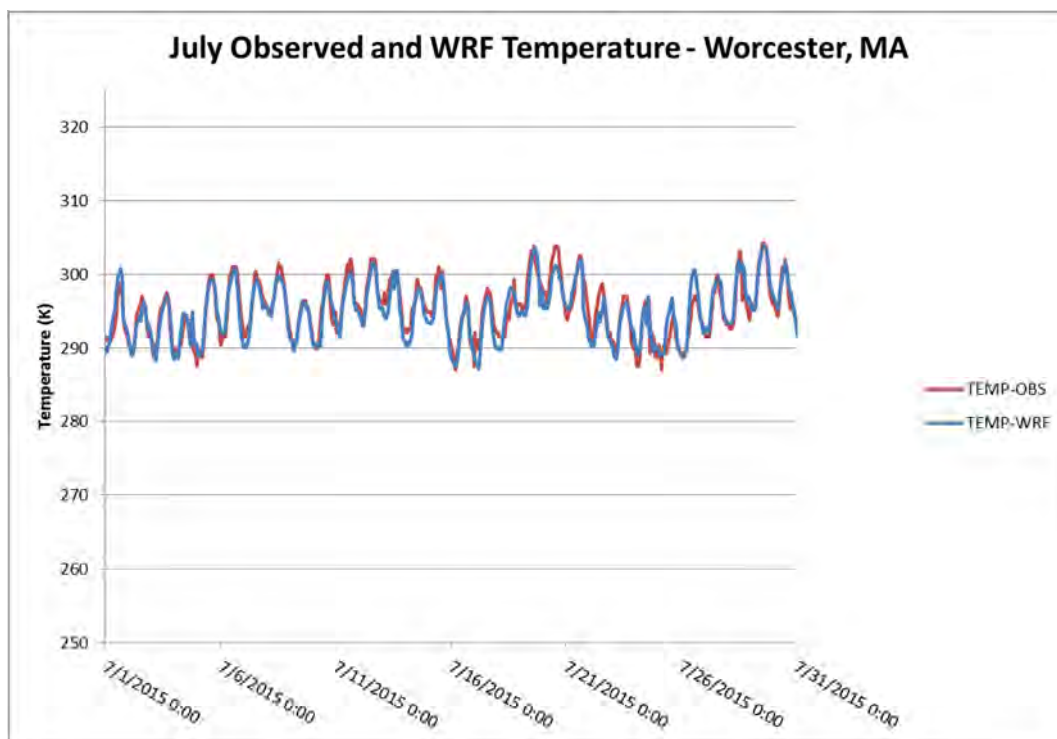


Figure 27 Observed and modeled temperature for Worcester July 2015.

1808644.000 - 2691

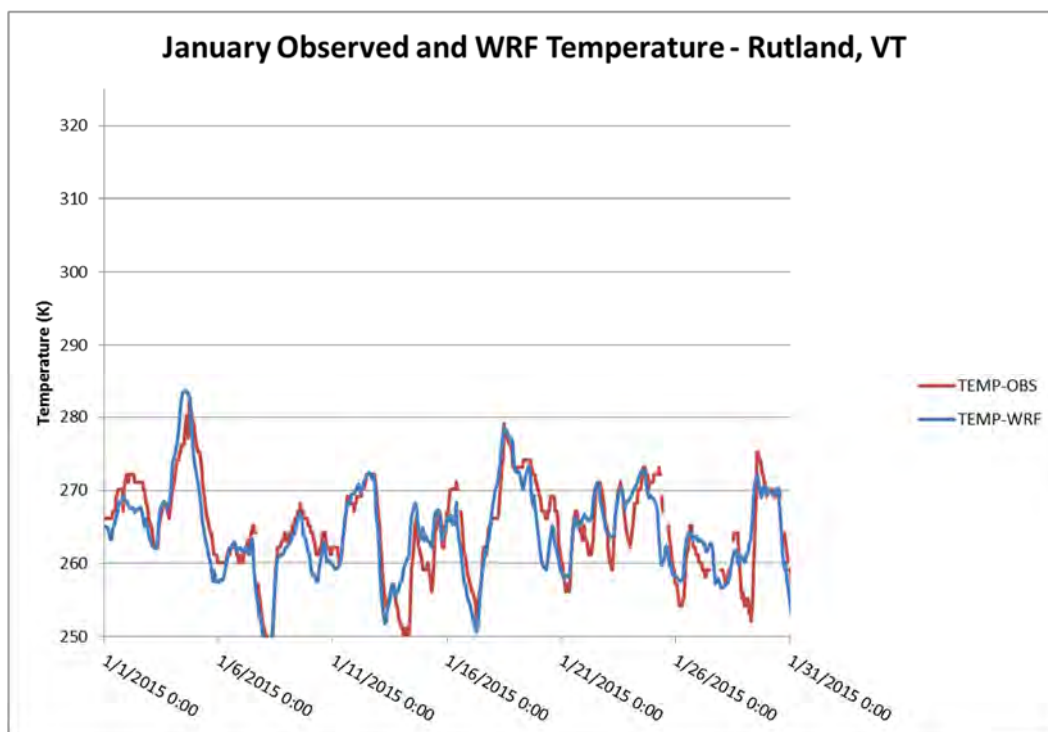


Figure 28 Observed and modeled temperature for Rutland, VT January 2015.

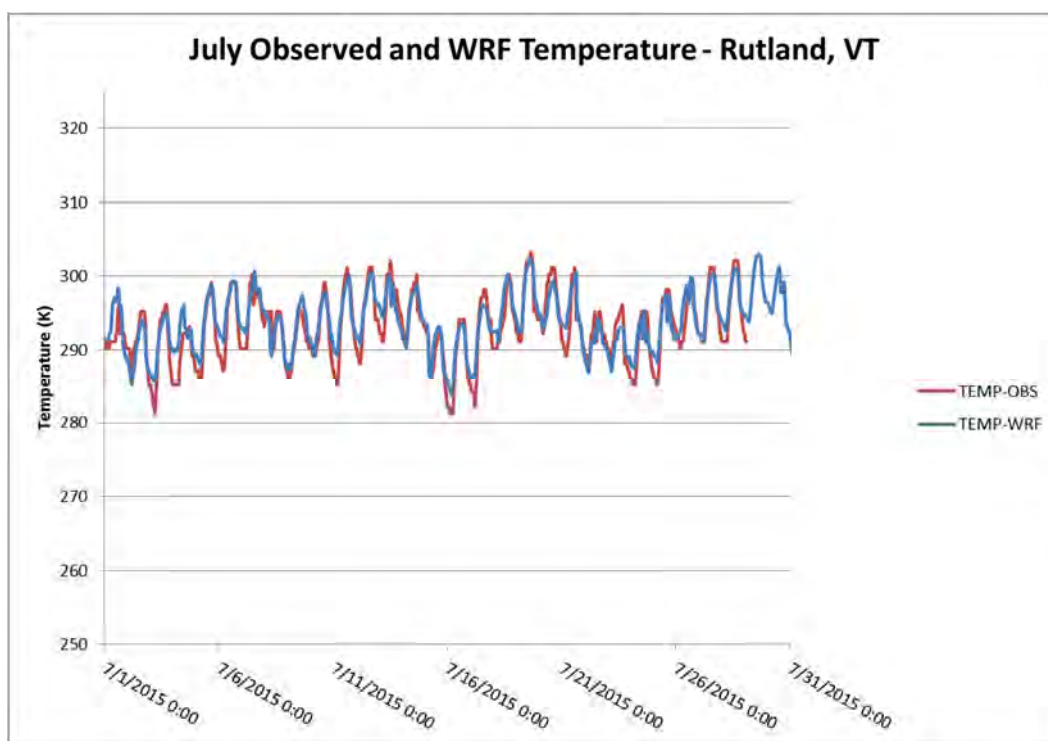


Figure 29 Observed and modeled temperature for Rutland, VT July 2015.

1808644.000 - 2691

2.3.3 Specific Humidity

The final analysis considers model performance for specific humidity. A summary of the evaluation statistics for temperature are presented in Table 7. IOA, Bias values and Gross Errors are within the performance benchmarks. While all of the results show good performance, coastal stations receive slightly lower scores when compared to inland or overwater stations.

Time series of specific humidity for January and July 2015 are shown in Figure 30 through Figure 35. Winter model predictions match well with observations. During the summer there is a tendency for the model to over predict daytime humidity levels. This behavior is common across all three stations analyzed.

It should be noted that the use of humidity in the CALPUFF model is in the chemical transformation modules which are not being applied in this application. Humidity is also used when calculating the overwater mixing height in CALMET (which is being bypassed through direct use of WRF data in this application), and as part of visibility calculations in CALPOST which are not being applied here. As a result, humidity has very little if any influence on the simulations performed in this analysis.

2.3.4 Conclusions

The WRF simulations provide reliable representations of meteorological parameters important for air dispersion modeling. Wind speeds, wind directions, temperature and specific humidity are well within the range of the benchmarks for good model performance. Further analysis demonstrates that the distribution of winds reliably reproduces the regional conditions and diurnal profiles of modeled parameters and are well matched during sampled winter and summer months. The simulations will provide an accurate annual distribution of meteorological conditions which will be important when calculating the annual average NO₂ concentrations for comparison with the Class I SIL.

Table 7. Statistical Model Performance for Specific Humidity

		Specific Humidity		
	Year	IOA -	Mean Bias g/kg	Gross Error g/kg
Benchmark		≥ 0.6	$\leq \pm 1$	≤ 2
All Surface	2015	0.65	0.95	1.53
	2016	0.64	0.92	1.50
	2017	0.64	0.88	1.45
Coastal Surface	2015	0.57	1.26	1.68
	2016	0.57	1.11	1.59
	2017	0.57	1.08	1.53
Inland Surface	2015	0.65	0.79	1.46
	2016	0.62	0.83	1.46
	2017	0.63	0.77	1.40
Over Water	2015	0.57	0.18	1.16
	2016	0.56	0.56	1.25
	2017	0.42	0.23	1.19

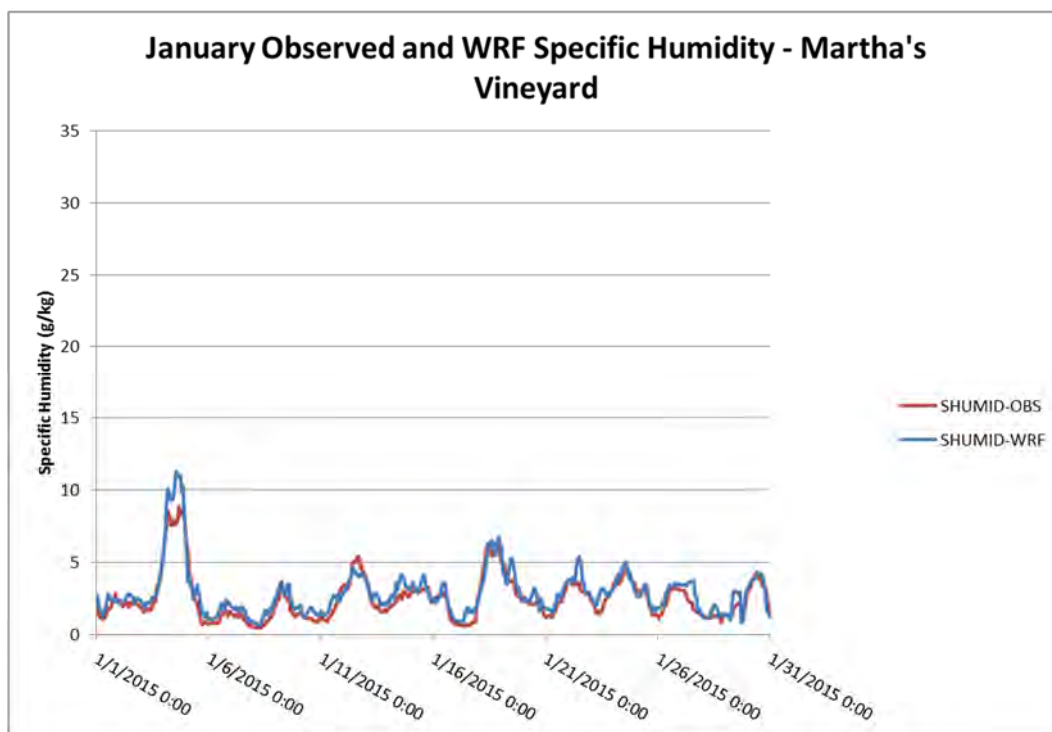


Figure 30 Observed and modeled humidity for Martha's Vineyard January 2015.

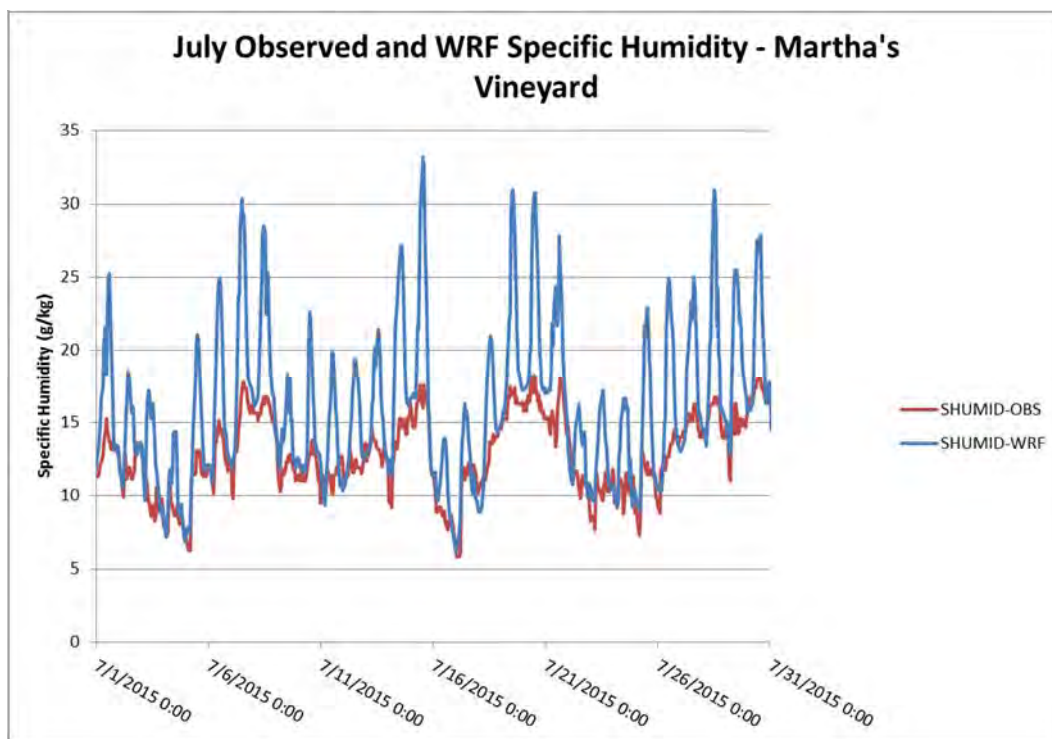


Figure 31 Observed and modeled humidity for Martha's Vineyard July 2015.

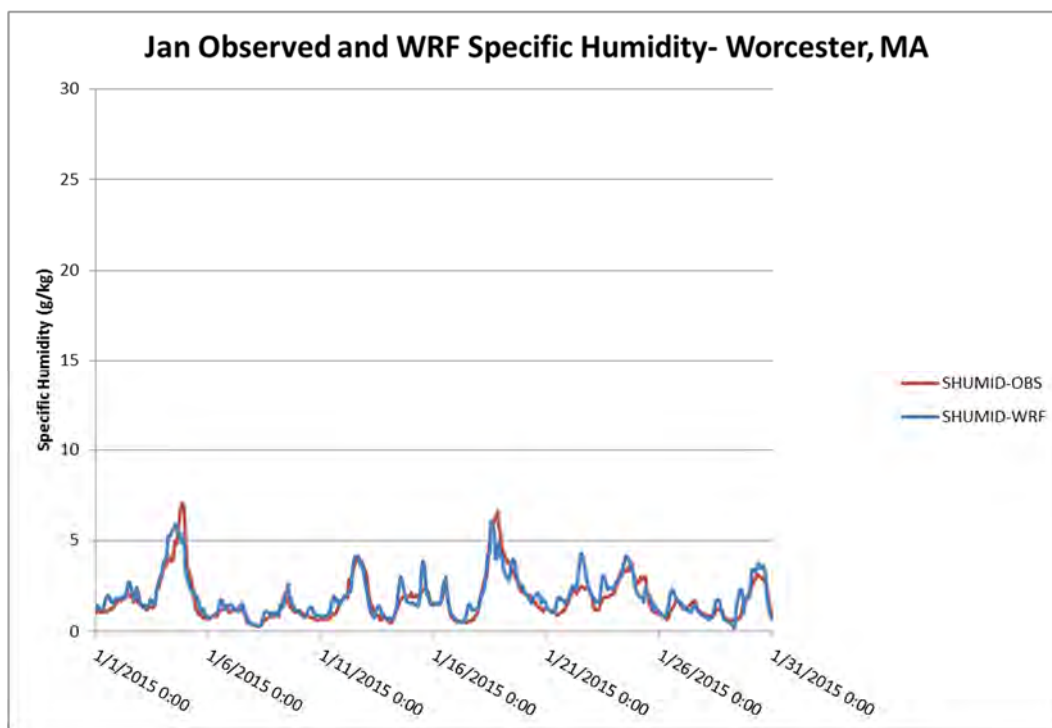


Figure 32 Observed and modeled humidity for Worcester January 2015.

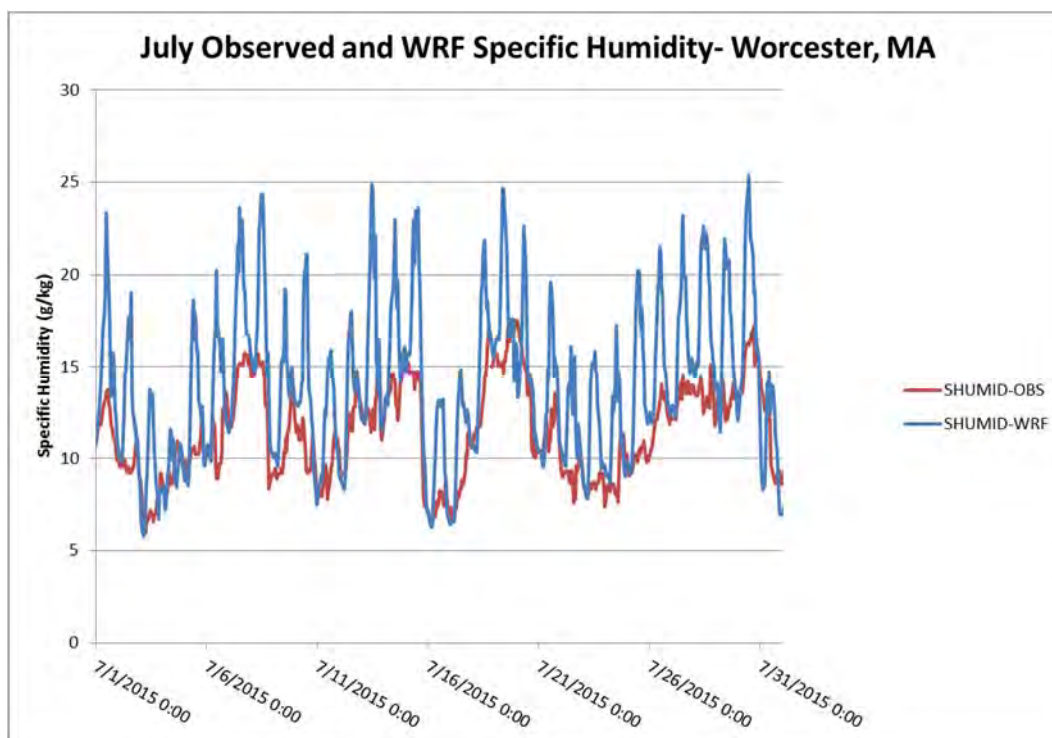


Figure 33 Observed and modeled humidity for Worcester July 2015.

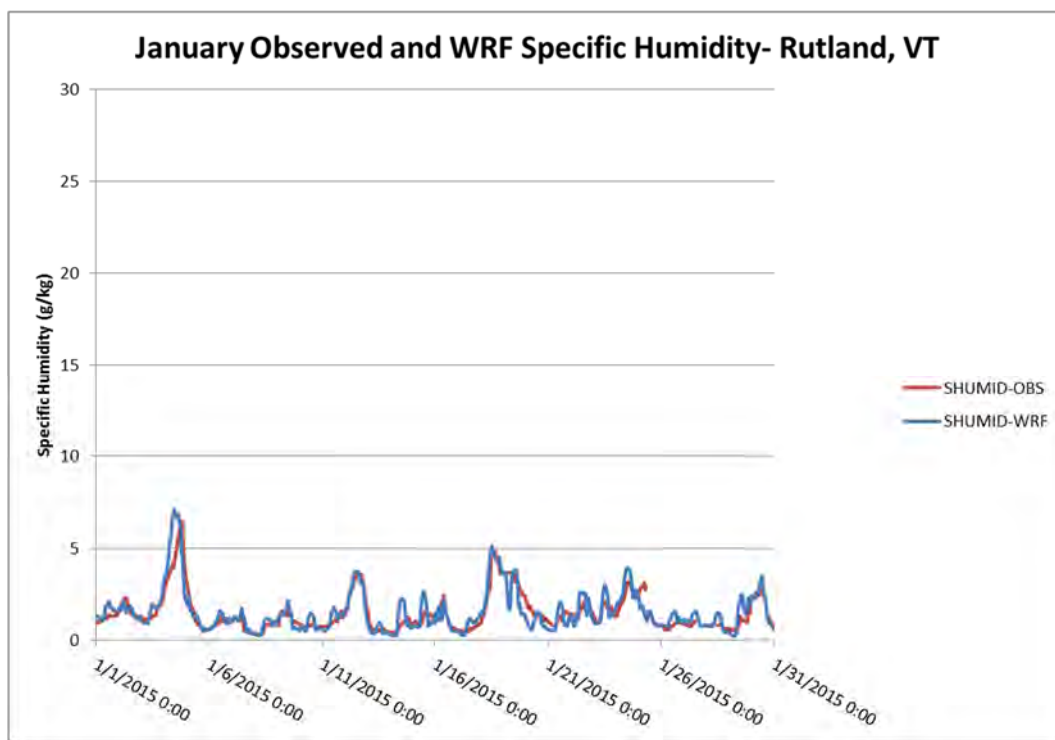


Figure 34 Observed and modeled humidity for Rutland, VT January 2015.

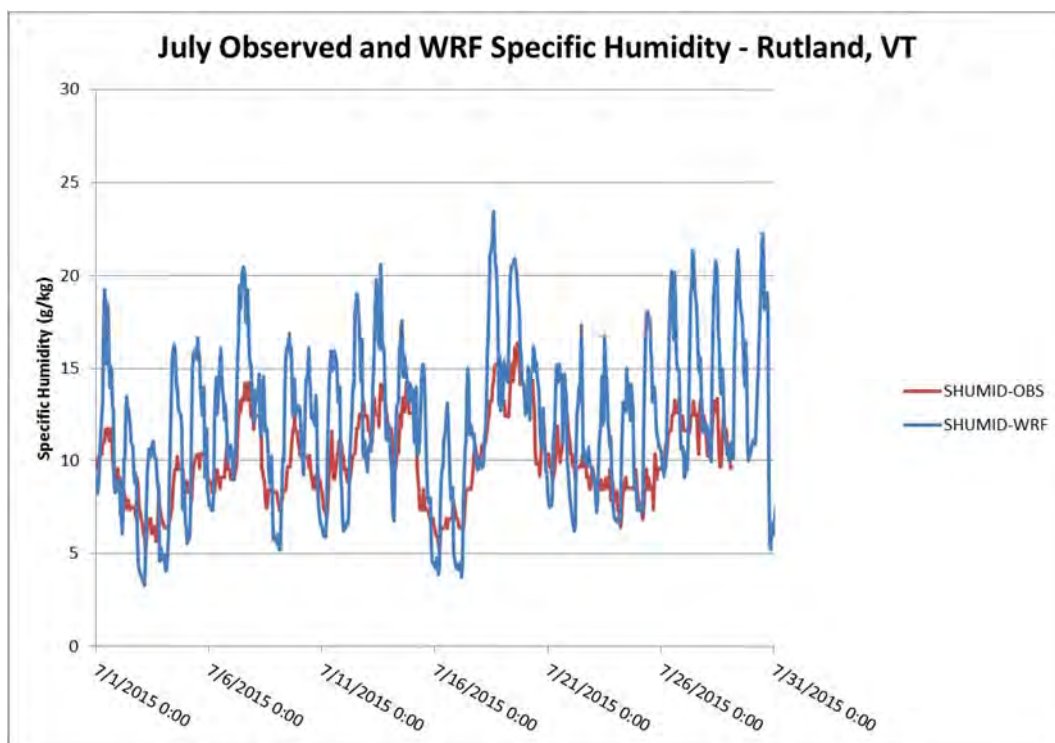


Figure 35 Observed and modeled humidity for Rutland, VT July 2015.

3 References

- Emery C., E. Tai, and G. Yarwood, 2001: Enhanced meteorological modeling and performance evaluation for two Texas ozone episodes. ENVIRON International Corporation, 101 Rowland Way, Suite 220, Novato, CA.
- FLAG, 2010. Federal Land Managers' Air Quality Related Values Workgroup (FLAG). Phase I Report—Revised 2010. U.S. Forest Service, National Park Service, U.S. Fish and Wildlife Service.
- Hosker, R.P., 1974: A comparison of estimation procedures for overwater plume dispersion. Proceedings of the Symposium on Atmospheric Diffusion and Air Pollution. American Meteorological Society, Boston, MA.
- McNally, D., Wilkinson, J.G., 2010: The MMIFstat Statistical Analysis Package Preliminary Draft Users Manual.
- Scire, J.S., D.G. Strimaitis, and R.J. Yamartino, 2000a: A User's Guide for the CALPUFF Dispersion Model (Version 5). Earth Tech, Inc. Concord, MA.
- Tesche, T.W., D.E. McNally, C.A. Emery, E. Tai. 2001: Evaluation of the MM5 Model Over the Midwestern U.S. for Three 8-hour Oxidant Episodes, Prepared for the Kansas City Ozone Technical Workgroup, by Alpine Geophysics, LLC, Ft. Wright, KY, and ENVIRON International Corp., Novato, CA.
- Wilmont, C. J., 1981: On the validation of models, *Phys. Geogr.*, 2, 168-194.

Appendix

Lakes WRF Model Documentation

LAKES ENVIRONMENTAL WRF MODELING

1	Introduction	1
2	WRF Description	1
3	WRF Processing Specifications	2
3.1	Input of Meteorological Data	2
3.2	Nested Grids Domains.....	2
3.3	WRF Physics Options	4
3.4	Additional WRF Modeling Information	5
3.5	WRF Output for AERMET	5
3.6	WRF Output for CALMET	6
4	Additional Information	7

1 Introduction

This document provides a brief description of WRF modeling at *Lakes Environmental* and the type of outputs generated. Our WRF modeling focuses on generating high resolution data with enough information to create meteorological input files for the CALPUFF and AERMOD modeling systems.

2 WRF Description

The Weather Research and Forecasting model (WRF) is a prognostic meteorology model developed in a collaborative partnership between the U.S. National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP), and others. The WRF model is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation.

3 WRF Processing Specifications

3.1 Input of Meteorological Data

WRF does not directly use conventional meteorological data from airport reports. Instead, the model uses objective analysis of global weather reports. Objective analysis is a process of analyzing the observed data and outputting them into a regular grid. The meteorological field is “balanced” to account for the energy and momentum equations of the atmosphere. These objective analyses are products of global models, which are maintained by national weather centers or federal agencies such as UKMO (United Kingdom Meteorological Office) or US NCEP.

Lakes Environmental used the NCEP Global Forecast System (GFS) 0.5-degree resolution data (approximately 50-km resolution) for input into WRF. GFS 0.5-deg data is given every 6 hours at 00, 06, 12, and 18Z.

Sea Surface Temperature (SST) data comes from the GFS 0.5 degree data but updated daily as each WRF simulation is done for 24 hours.

3.2 Nested Grids Domains

WRF uses a nested grid approach allowing an area of interest to be modeled without the penalty of excessive run times created by having a fine grid over the entire modeling domain. Depending on the application, Lakes Environmental employs 12-km, 4-km, or 1-km grid spacing at the highest resolution (inner grid).

Tables 1 & 2 present the grid dimensions and number of grid points that are commonly used.

Table 1a. WRF Nested Domain Grids – 12km & 4km Orders, 50x50km Domain

Domain	Resolution (km)	Number of Grid Points in X and Y
Domain 1	108	31 x 31
Domain 2	36	31 x 31
Domain 3	12	31 x 31
Domain 4 (if necessary)	4	31 x 31

Table 1b. WRF Nested Domain Grids – 12km & 4km Orders, 100x100km Domain

Domain	Resolution (km)	Number of Grid Points in X and Y
Domain 1	108	40 x 40
Domain 2	36	40 x 40
Domain 3	12	40 x 40
Domain 4 (if necessary)	4	40 x 40

Table 2a. WRF Nested Domain Grids – 1km Orders, 50x50km Domain

Domain	Resolution (km)	Number of Grid Points in X and Y
Domain 1	27	73 x 73
Domain 2	9	73 x 73
Domain 3	3	73 x 73
Domain 4	1	73 x 73

Table 2b. WRF Nested Domain Grids – 1km Orders, 100x100km Domain

Domain	Resolution (km)	Number of Grid Points in X and Y
Domain 1	27	121 x 121
Domain 2	9	121 x 121
Domain 3	3	121 x 121
Domain 4	1	121 x 121

3.3 WRF Physics Options

The WRF model provides many modeling options which can greatly affect the final output. In Table 3 below, we have listed the physics options most commonly used for the WRF processing.

Table 3. Physics Options Used for WRF Modeling

WRF Physics Options		
#	Type	Options Used
1	Microphysics	WRF Single-moment 6-class scheme mp_physics = 6
2	Long-wave Radiation	RRTMG Longwave scheme ra_lw_physics = 4
3	Short-wave Radiation	RRTMG Shortwave scheme ra_sw_physics = 4
4	Surface Layer	Eta Similarity scheme sf_sfclay_physics = 2
5	Land Surface	Unified Noah Land Surface model sf_surface_physics = 2
6	Planetary Boundary Layer	Mellor-Yamada-Janjic (MYJ) scheme bl_pbl_physics = 2
7	Cumulus parameterization	Kain-Fritsch (grid size > 10km only) cu_physics = 1

See link below to the UCAR web site for descriptions and references of WRF physics options:

http://www2.mmm.ucar.edu/wrf/users/phys_references.html

3.4 Additional WRF Modeling Information

The information below describes other modeling parameters taken into account for *Lakes Environmental* WRF processing:

- WRF-ARW and WPS models Version 3.7.1
- Map projection in Lambert Conformal Conic (LCC)
- 35 ETA vertical pressure levels
- USGS 24 land use category data

In addition to the above options, a spin up time of 6 hours for each daily run was used. This means that every 24-hour run was composed of 30 hours where the 6 preceding hours are used for proper daily initialization. The initialization process discards these 6 initial hours which are not saved in the output as part of the meteorological modeling run.

3.5 WRF Output for AERMET

The US EPA Mesoscale Model Interface Program (MMIF) is a tool that retrieves data from NCAR's WRF-ARW model output in netCDF format and generates surface and upper air data files that can be used by the US EPA AERMET model (meteorological pre-processor for the US EPA AERMOD air dispersion model).

Data for use in AERMET/AERMOD are extracted from the innermost domain for the center of the grid cell closest to the user-defined latitude/longitude coordinate. Outer domains are used only to provide information to the innermost domain.

The latest version of the MMIF program is used. Table 4 contains a description of the files that were generated by the MMIF program where METxxxxxx is the order number, yyyy is the starting year, and zzzz is the ending year.

Table 4. Files Generated by MMIF

#	File Name	Description
1	METxxxxxx_AERMET_yyyy-zzzz.IN1	AERMET Stage 1 Input File
2	METxxxxxx_AERMET_yyyy-zzzz.IN2	AERMET Stage 2 Input File
3	METxxxxxx_AERMET_yyyy-zzzz.IN3	AERMET Stage 3 Input File
4	METxxxxxx_AERMET_yyyy-zzzz.DAT	Onsite Surface Met File
5	METxxxxxx_AERMET_yyyy-zzzz.FSL	FSL Upper Air Met File

3.6 WRF Output for CALMET

CALWRF is a tool that retrieves data from NCAR's WRF-ARW model output in netCDF format and creates a 3D.DAT file suitable for input into the CALMET model. The CALWRF output forms a grid covering the requested modeling domain with the requested resolution of either 1 km, 4 km, or 12 km. CALMET is a 3-D diagnostic meteorological pre-processor for CALPUFF model. CALPUFF is an advanced non-steady-state air quality dispersion model. CALWRF, CALMET, and CALPUFF are from Exponent. See below additional information on the CALWRF executable currently in use at Lakes Environmental:

- CALWRF.EXE, Version 2.0.1, Level 130418
- Generates 3D.DAT file in Version 2.1 format

The output from CALWRF is an ASCII file, known as the 3D.DAT format, which contains output variables for each hour, for each pressure level, and for each grid cell. Table 5 below describes the output variables.

Table 5. Variables Available in 3D.DAT File

#	Parameter	Units
1	Pressure	(mb)
2	Elevation	(m above mean sea level)
3	Temperature	(K)
4	Wind direction	(deg)
5	Wind speed	(m/s)
6	Vertical wind velocity	(m/s)
7	Relative humidity	(%)
8	Vapor mixing ratio	(g/kg)
9	Cloud mixing ratio	(g/kg)
10	Rain mixing ratio	(g/kg)

In addition, Table 6 describes the surface variables reported for each hour and each grid cell under the 3D.DAT file.

Table 6. Surface Variables Available in 3D.DAT File

#	Parameter	Units
1	Sea level pressure	(hPa)
2	Total rainfall accumulated for the past hour	(cm)
3	Snow cover indicator	-
4	Short wave radiation at the surface	(W / m ²)
5	Long wave radiation at the top	(W / m ²)
6	Air temperature at 2 m	(K)
7	Specific humidity at 2 m	(g/kg)
8	Wind direction of 10 m wind	(deg)
9	Wind speed of 10 m wind	(m/s)
10	Sea surface temperature	(K)

3.7 WRF Output for CALPUFF

The Mesoscale Model Interface Program (MMIF) converts prognostic meteorological model output fields to formats required for direct input into dispersion models. The utility was developed by ENVIRON International Corporation for the USEPA and is distributed via the USEPA's website. The utility reads data from NCAR's WRF-ARW model output in netCDF format and creates data in a user-specified format. The latest version of the MMIF program is used.

MMIF can be used to generate data for direct input to the CALPUFF model bypassing the CALMET model entirely. Output can be processed for use in either CALPUFF version 5.8.x or CALPUFF version 6 / 7. MMIF generates three sets of files:

- **Projection File:** This file contains information on the domain, projection, and met grid to be used in the CALPUFF project.
- **Terrain Grid File:** This is a gridded file containing terrain elevations (from mean sea level) to be used in the extraction of base elevations for sources and receptors in the CALPUFF project.
- **CALPUFF-Ready Meteorological Data Files:** The meteorological data to be input to CALPUFF.

4 Additional Information

If you require any further information, please contact us at support@webLakes.com. When contacting us, please provide the met data order number.

For more information about the WRF meteorological model, please visit the site below:

<http://www.wrf-model.org/index.php>